EXPLORATION AND ESTIMATION OF GRAVEL RESOURCE POTENTIAL IN SOUTHEAST CHUKCHI SEA CONTINENTAL SHELF OFF KIVALINA, AK

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December 15, 2005

Date

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A

THESIS

Presented to the Faculty of
the University of Alaska in Partial
Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Fairbanks, Alaska
December 2005

ABSTRACT

Frequent storm surges in the Alaskan arctic result in washovers and high erosion of barrier islands. The village council of Kivalina has resolved to relocate from its present location on a barrier island in Northwest arctic Alaska to an adjacent onshore site. The relocation plan envisages excavation of upper 4 meter of the 25 km^2 onshore permafrost ground and construction of a foundation pad. The objective of this research is to estimate the gravel resource potential in the continental shelf off Kivalina. In this context seismic surveys and sediment sampling were conducted. The seismic surveys were of limited use as they failed to resolve the upper 1-2 m of the seafloor. The lithostratigraphy indicated dominance of the 2.4-3.4 mm size fraction in the region north of Kivalina. The geostatistical analysis indicated an omnidirectional variogram fit to the data with ordinary kriging producing the best kriging estimate of the gravel resource potential. At least 20×10^6 m^3 of gravel above the 90 % cut-off is present in the upper 0.5 m of the seafloor. The regional Pleistocene glaciation has affected the lateral variations in gravel abundance in the nearshore southeast Chukchi Sea.

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ACKNOWLEDGEMENTS

This research was funded by the Minerals Management Service of the United States Department of Interior.

My sincerest thanks go to my advisor Dr. Sukumar Bandopadhyay for giving me a research assistantship, thus giving me this wonderful opportunity to work on this project. His support, guidance and enthusiasm during these two years will always be an inspiration to me. Thanks are also due to my co-advisor Dr. Sathy Naidu, under whom I worked most of the time, for his dedication to the project and for his invaluable words of wisdom. I also thank my committee members Dr. John Kelly and Dr. Rajive Ganguli for their constant feedback and constructive criticism.

I also thank the crew of R/V *Alpha Helix*, Golder Associates (Seattle), and Innerspace Exploration Team (Seattle) for their help in conducting the geophysical survey and the geological sampling part of the project. I also thank Prof. Daniel Walsh and Dr. Steve Saboundjian for their help in the particle size analysis and the geotechnical analysis respectively.

My special thanks go to my colleagues and all my friends for their tremendous help and cooperation during my stay at Fairbanks. Finally, but not the least, I thank my family for everything they have done for me.

Chapter 1
INTRODUCTION

1.1 Background

Sand, gravel and crushed stone are together known as aggregates and are necessary raw materials for infrastructure development. Aggregates are the largest non-fuel mining industry in the United States accounting for two-thirds of the non-fuel production. The value of aggregates dwarf other non-fuel commodities such as gold ($2.9 billion), copper ($2 billion), iron ($1.2 billion), and salt ($1 billion) to name a few (Langer, Drew, Sachs, 2004). Sand and gravel are mined together and hence the exact production estimate for gravel in the United States is unknown. In 2003, the country produced 1.2 billion metric tons of sand and gravel worth $ 6 billion and exported $ 25 million worth of sand and gravel in the same year. Forty-four percent of all sand and gravel came from the west, with California alone producing $1.16 million worth of sand and gravel, while the northeast contributed the least, 11% of the total production. More than three billion tons of aggregate were produced in the U.S in 2004 at a value of approximately $ 16 billion (National Sand, Stone and Gravel Association, 2005). The country's dependency on aggregates for technological progress will continue into the twenty-first century with an estimated 100 billion tons of aggregates expected to be used during the next 25 years (Langer, Drew, Sachs, 2004).

Offshore gravel mining is an established industry in Japan, United Kingdom, Netherlands, Belgium and Denmark with the last four countries having a production of about 230 million tonnes in 2000 (Harrison, 2000). The principal uses of marine aggregates are in the concrete industry, beach nourishment projects, and the coastal reclamation industry. The United States is dependent on its land-based sources for almost all of its gravel resources. The United States' use of offshore gravel is limited to state waters off New Jersey, New York, Florida, Mississippi and California (U.S Congress, 1987). In Alaska, offshore gravel is used to construct islands for hydrocarbon drilling operations (Williams, 1991). Any serious exploration for gravel is still in its nascent stages, limited by technological, economical, and environmental constraints. However with land deposits diminishing, there is a need to explore offshore deposits in order to meet the demands for gravel and aggregates in the future.

Numerous studies on the sediment characteristics of the outer continental shelf of Alaska have indicated presence of gravel along with sand and mud (Creager and McManus, 1966, Stauffer, 1987, U.S Congress, 1987). The 1987 U.S Congress report on marine minerals provides qualitative information on the availability of gravel deposits in the U.S Exclusive Economic Zone. Included in the report are deposits which are in waters of 40 m or less. However, not much is known about the grain size distributions of the gravel deposits.

The Alaskan Continental Shelf covers 76 % of the total shelf area of the United States. There are a lot of potential gravel deposits in the Alaskan offshore region. Mining gravel resources is currently not feasible for the following reasons (U.S Congress, 1987):

1. Much of the glacial gravel is poorly sorted
2. Gravel deposits are overlain by sandy and muddy layers

With the sea level expected to rise 70 cm in the next 100 years (Intergovernmental Panel on Climate Change, IPCC, 2001; Day, 2004), erosion of coastlines will be a major problem not only in Alaska but worldwide. Hence beach nourishment projects designed to minimize erosion will require large volumes of sand and gravel. Offshore areas will become a logical source for the fill material because of their proximity and ready availability. It is likely that future supply of coarse aggregate in Alaska may involve exploitation of marine deposits. The Chukchi Sea is a potentially favorable region for this type of mining because of extensive deposits of paleo beach and other relict gravel found in the near shore region (Stauffer, 1987). However a systematic analysis of the potential gravel resource has not yet been conducted and it is the purpose of this research to estimate the size, extent and variability of gravel material that may be available in the continental shelf, offshore Kivalina.

1.2 Scope of the problem

The circum-arctic coasts, including those in Alaska, have some of the highest rates of coastal erosion (1-20 m y^{-1}) in the world, primarily because of combined impacts of thermo-erosion and storm surges on permafrost-dominated, unconsolidated deposits of shorelines. The high erosion and storm surges are deleterious to coastal communities. Kivalina, which is situated on a barrier island in the southeast Chukchi Sea, is exposed to these natural hazards. To address this chronic problem and to find a long-term solution, the Kivalina village council resolved to relocate the village from the barrier island to an adjacent onshore site (The Associated Press, 2001).

However, the coastal plain identified for the village relocation has continuous permafrost, posing an unstable ground for erecting houses and infrastructures, which calls for special foundation measures. The relocation plan envisages that the active permafrost ground (estimated ~ 25 km^2) will be excavated to a depth of 4 m and filled with gravel. A region targeted as a potential source for the large volume of gravel needed is the continental shelf adjacent to Kivalina.

1.3 Objective of the study

The main objective of the thesis is to provide an estimate of the marine gravel resource potential in the Kivalina area. From a mining point of view the hypothesis tested was that there are potential gravel deposits in the region of sufficient volume and quality to meet the future needs. The regional Pleistocene glacial-interglacial history is closely linked to the occurrence of gravel deposits. The second hypothesis tested in this thesis is that the glaciers during the Pleistocene were agents for the transport and deposition of gravel in the subsurface seafloor of the Alaskan Arctic.

Exploration of the gravel resource potential consisted of seismic surveys followed by seafloor sediment sampling in the Cape Thompson-Kivalina area. A brief review of gravel occurrences is given in Chapter 2. The seismic survey and the sediment sampling methods are described in the first sections of Chapter 3. Geostatistical modeling and geotechnical analysis are presented in the later sections of Chapter 3.

Chapter 2

LITERATURE REVIEW

2.1 Gravel and its occurrences

Gravel is a clastic mineral derived from igneous, sedimentary or metamorphic rocks by the erosive forces of water and ice. It is generally found in conjunction with sand, silt and clay. The definition of gravel in geological studies follows the Udden-Wentworth scale of size grades, according to which gravel is any clastic material greater than 2 mm. The American Society for Testing and Materials (ASTM) defines gravel as any granular material retained on the No. 4 (4.75-mm) sieve that results from natural disintegration and abrasion of rock or processing of weakly bound conglomerate. Gravel is used as aggregate in buildings, as a road base and covering, in asphaltic concrete and other bituminous mixes, as railroad ballast, and for snow and ice control among many uses (Langer, 1993). However marine gravel is currently mined mostly for beach nourishment, gravel pad construction and other offshore construction projects (Oele, 1990).

Sand and gravel debris are accumulated by the actions of glaciers and marine processes. There are two types of offshore gravel deposits. Active deposits are those which are continuously subjected to change, and inactive deposits are those which have been formed during lowered sea levels of the Pleistocene period. Active deposits are unlikely to be mined for gravel as it might affect ongoing water dynamics and impact sediment transport.

The physical mechanisms that cause accumulations of gravel in the offshore region are mainly waves, currents, and ice. Table 2.1 shows the natural mechanisms for transporting and depositing gravel.

Table 2.1 Natural mechanisms for transporting and depositing gravel (Stauffer, 1987)

Physical Agency	**Maximum Particle Size**	**Sorting in Deposits**	**Depths Limits in Sea**	**Possible Examples of Deposits**	
				Offshore	**Nearshore**
Grounded Glacial ice	No limit	Very poor	~130 m + 9/10 ice thicknes s	Pleistocene Moraines	Pleistocene and Holocene moraines
Floating glacial ice	No limit	Very poor for clasts larger than those moved by currents	None	Quaternary glacial marine sediments	Pleistocene glacial marine sediments
River water flow	Commonly silt to gravel	Moderate	~130 m +channel depth	Pleistocene channel fill	Estuarine and river mouth deposits
Marine bottom currents	Commonly silt to fine gravel	Good	~130 m + 200 m	Sand waves, ripples, leeside shoals, winnowed lags	Intertidal sand bars
Surface wave action	Fine sand to cobbles	Good to excellent	~130 m + 'Wave base'	Symmetrical sand waves, ripples	Beaches, offshore bars
Subaqueous mass movements	No limit	Unchanged in cohesive slides to moderate in turbidity current deposits	None	Turbidities, mass-flow deposits, slide masses	Sand flows

According to Stauffer (1987) floating ice is the principal agent for transporting and depositing gravel in a high-latitude marine environment. The sorting produced by this mechanism is very poor and the coarse material is often diluted by fine grained sediment transported to the site by ice or other means. In the sea the transport and deposition of coarse material also results from wave action, bottom currents, and sediment gravity flows. The sorting imparted by the latter mechanism often ranges from good to excellent.

Not all present sea floor gravel deposits were deposited by marine processes (Stauffer, 1987). During the Pleistocene, a large part of the present shelf was land. The shoreline was about 120 m offshore from where it is today. Most glacio-fluvial deposits were formed offshore of the present shoreline during this lowered sea level and are now part of the paleo deposits of the sea floor. These deposits, though not well sorted, can have large lateral extents which make them good sources for natural aggregates. For any aggregate source to become useful in construction purposes it has to be poorly sorted, i.e. it should contain a large variety of grain sizes.

The techniques for marine gravel exploration are slightly different than those used on land. There are two types of techniques: Physical sampling and remote sensing by acoustical sounding. Unlike on land, physical coring of the seafloor substrate is not always possible due to adverse sea conditions and compact substrate. A variety of methods for sea floor sampling, like grab samplers, box corers, and dredge samplers have been developed. If coring is to be done, then vibracoring is the most inexpensive option, although the penetration in deposits containing cobbles and boulders is poor. Rotary drilling is an expensive method, but it provides excellent penetration in a hard substrate. Acoustical surveys can be achieved by surface towed sounding devices. Among the surface towed methods, seismic reflection is the most common method used. The resolution achieved by this method is, however, a function of various factors like the frequency of the pulse, and resolution of the hydrophones. Sub-bottom profilers and side scan sonars are used to map the sea floor surficial sediment texture and features.

2.2 Area of Study

Kivalina is at the tip of a 13 km barrier island located between the Chukchi Sea and Wurlik River (Fig 2.1). It is located approximately 130 kilometers north of the Arctic Circle on the Chukchi Sea coast. This low lying island is subject to flooding during occasional storm surges and erosion due to wave action (Scheffner and Miller, 1998).

Acoustic-reflection studies within the Hope Valley (the part of the shelf off Kivalina) indicated that the sediments overlying the basement rocks are up to 10 m thick (Moore, 1964). The Cape Thompson-Kivalina area contains gravel along the near shore (Stauffer, 1987; Creager and McManus, 1966). The gravels are probably relict glacial deposits, with the source being the De Long Mountain ranges.

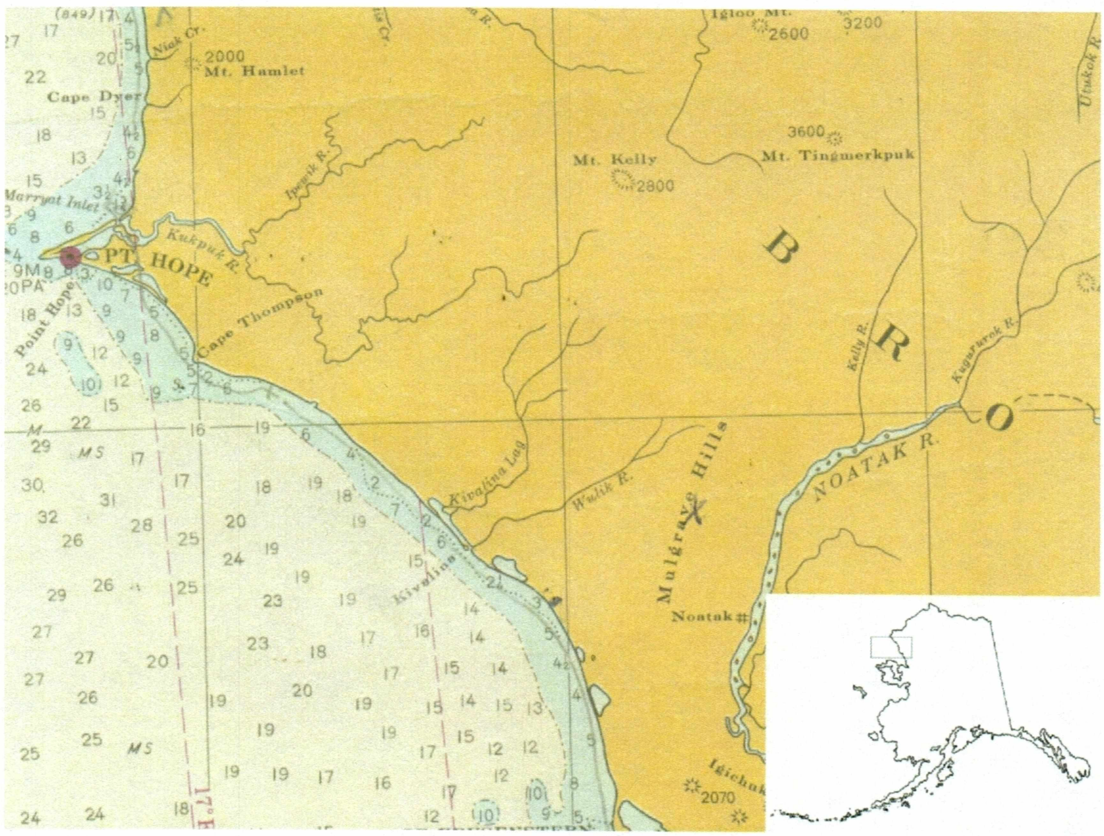


Figure 2.1 Map of the Cape Thompson-Kivalina area (After National Ocean Service, 2002)

Fig 2.2 shows the sediment distribution in the near shore of the region. It is evident that there are large gravel deposits in the region, but the quantity and extent of the gravel is not known.

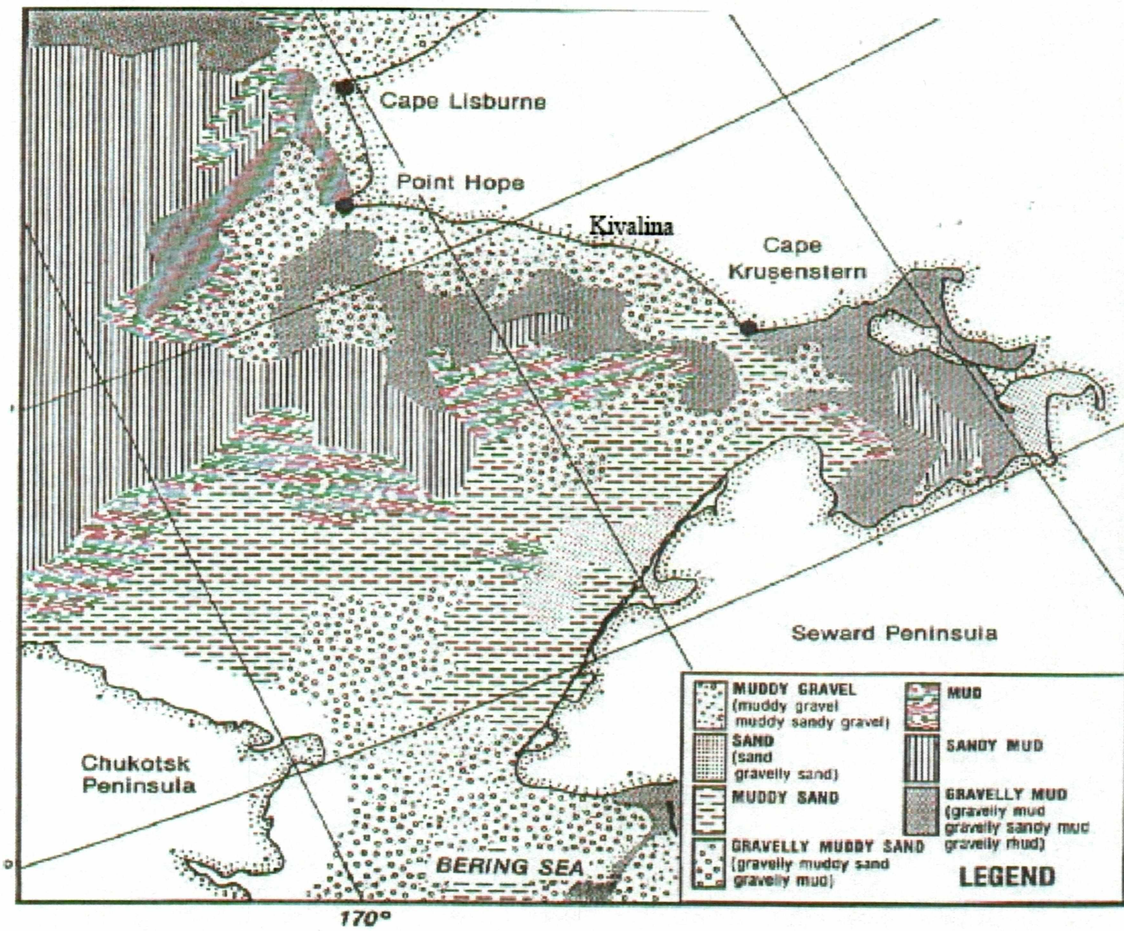


Figure 2.2 Distributional pattern of sediment classes in southeastern Chukchi Sea (After Naidu, 1988)

The above sediment maps do not provide quantitative information on the volume of gravel and on the particle size distribution, which are probably the most important characteristics from an engineering standpoint. Hence these maps are of limited use in gravel resource estimation, unless supplemented by further data. It is the purpose of this investigation to provide quantitative information on the gravel resource potential and the particle size distribution of the gravel deposit.

Chapter 3

MATERIALS AND METHODS

3.1 Introduction

The investigations presented here consist of two major tasks: one in the field and the other in the laboratory. The field operations consisted of a seismic survey and collection of grab samples and sediment cores, while the laboratory operations consisted of grain size analysis of the collected sediments and geotechnical testing of the gravel as well as geostatistical analysis for reserve estimation The field studies off Kivalina were conducted in August 2004 aboard the University of Alaska Fairbanks (UAF) research ship R/V *Alpha Helix*. The geophysical survey was conducted with the assistance of Golder Associates, Seattle and the vibra core sampling was completed with the assistance of Innerspace Exploration Team (IET), also from Seattle. The grain size analysis was conducted at the Mineral Industry Research Laboratory (MIRL) at the University of Alaska Fairbanks. The geotechnical analysis was conducted at Shannon and Wilson, Inc, Fairbanks. The geostatistical analysis was conducted at the computer laboratory at the Department of Mining and Geological Engineering at UAF.

3.2 Seismic Survey at Kivalina

3.2.1 Introduction

Geophysical methods are used for geological mapping of the gravel deposits and can be used to delineate gravel from sand and muddy deposits, but only after due processing of the data. For the exact nature of the surficial strata, physical methods are the only known means.

The seismic reflection technique is probably the best known geophysical method for prospecting coarse grained deposits. In marine geophysical studies, seismic reflection is preferred over other methods as the inability of water to transmit shear waves makes it possible to obtain high quality reflection data at shallow depths which is not possible on land. Seismic reflection data will give information on the thickness of coarse grained layers which can then be confirmed by physical sampling. The bubble pulse method is the most common seismic method in marine aggregate prospecting because of its ability to achieve subsurface penetration in coarse-grained compacted sediment that is not possible with conventional sub-bottom profilers or higher frequency energy sources. Therefore for the investigations the bubble pulse seismic method was used.

3.2.2 Geophysical survey

Briefly, the seismic survey method for recording the sub-bottom stratigraphy and geological structures consisted of the following. The survey consisted of continuous subsurface reflection profiling using acoustic pulses, emitted at regular intervals by an energy source and transducer (Fig. 3.1). The high-resolution seismic reflection data were collected with a Datasonic Bubble Pulser System (Fig.3.1). This relatively low frequency system (350 to 800 Hz) can achieve subsurface penetration in coarse-grained compact sediment that is not possible with conventional sub-bottom profilers or higher frequency energy sources. At the study site, the maximum subsurface penetration achieved with this system was about 91 m below the seafloor. The Bubble Pulse transducer was towed on the port side of the survey vessel, and the hydrophone streamer was towed from the starboard side of the vessel. Both instruments were approximately 23 m astern of the GPS antenna.

The transmitted acoustic pulses were reflected from the seafloor and underlying stratigraphic horizons. The reflections were then successively received by hydrophone streamers (Fig. 3.1) towed on the water surface, which converted the acoustic pressure waves into electric signals. The acoustical signals were processed and displayed on a graphic recorder and stored digitally for post processing. The graphic display or continuous reflection record consisted of an acoustical profile of the seafloor, sub bottom stratigraphy and geologic features along the survey track line.

An integrated and automated navigation system was used for on-line navigation and positioning of the survey vessel. This system consisted of a Trimble 400SE Differential GPS receiver and Raytheon INSTAR navigation software. The differential Global Positioning System (DGPS) was used to determine the vessel's location in real-time and to plot the position along the survey lines. The pre-plotted survey lines and the actual survey lines traversed by the vessels were displayed in real-time on a video monitor. The navigation computer transmitted event marks to the geophysical recording instruments every two minutes in order to correlate the geophysical data with the survey vessel position. The navigation data and event marks were digitally recorded and used to produce the survey track line map.

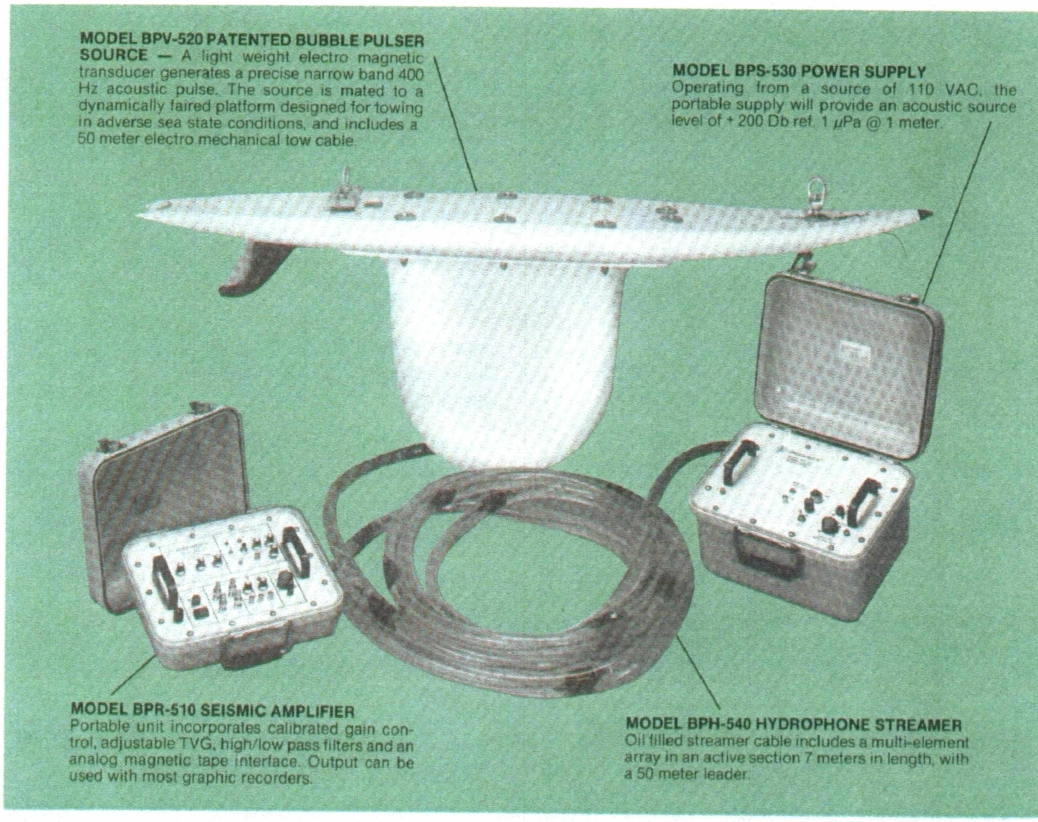


Figure 3.1 Seismic equipment used aboard the research vessel R/V *Alpha Helix* (After Sylwester, 2002)

The reflection data were processed with a Geo Acoustic Model 2800 processor and displayed on an EPC Model 1086-500 thermal graphic recorder. The graphic recorder was set for a display of 100 milliseconds, which is equivalent to a depth of approximately 91 m. The data were also archived on a Sony analog recorder and acquired with DPS Technology Dr. Geo, a digital acquisition and processing program. The time window recording for the data was 400 milliseconds. The graphic recorder, interfaced with the navigation computer by means of the RS232 input, printed vessel position and time at a 2-minute interval.

3.3 Sediment sampling at Kivalina

3.3.1 Introduction

Sampling for seafloor sediments can be conducted using several methods. The most commonly used sampling devices are grab samplers for surficial deposits and cores for subsurface samples (Poppe et al., 2004). Grab sampling by devices such as van Veen can result in biased sampling in two different ways; if the substrate is composed of pebbles and cobbles, then these might get stuck between the jaws of the samplers, resulting in washing away of the finer particles. Also, when sampling for gravel, the threshold weight of the sample required statistically increases with increases in the largest particle size. The necessary sample size is seldom achieved. Hence standard small grab samples can only be used as a semi-quantitative tool in offshore aggregate sampling.

To get information on the occurrence, variation and depth of coarse grained deposits under the seabed, coring is the preferred method. Coring in coarse substrate can be achieved by using two different methods: Rotary drilling and Vibra coring. Rotary drilling is the preferred approach for gravel sampling as it achieves good penetration even in cobble rich deposits and also provides indication of the depth of the deposits as it can also penetrate through bedrock. This method is expensive and can only be used if a stable platform is available. The vibra coring method is the most commonly used method for gravel sampling. Vibra coring can be accomplished by pneumatic, hydraulic or electric means. Cores as long as 6 m can be retrieved from shelf depths of up to 200 m (Williams, 1991). The coring can be conducted without a rigid platform and performs fairly well in finer gravel deposits. It performs poorly when the substrate contains cobbles and boulders. Due to the budgetary constraints we decided to go with vibra coring as the preferred sampling method.

Gravel sampling, if not conducted properly, is beset with problems of sampling bias and errors due to non-standardized data collection (Hack, 2002). Hack mentioned that drilling methods are the most preferred, in spite of some of their drawbacks. He also noted that grab sampling does not always constitute a representive sample from the area. However in the present investigation, substrate coring in rough seas and with hard substrate would be difficult and risky. Therefore grab samples, although biased towards the coarser end of the spectrum are the only means for reserve estimation and modeling.

3.3.2 Geological sampling

The sediment sampling was conducted in waters greater than 5 m depth. Based on the literature review, the area chosen is representative of the continental shelf off Kivalina. The decision to conduct the investigation in waters greater than 5 m depth is based on a practical rationale. If any significant gravel reserves were to occur in waters shallower than 5 m, dredging operations would lead to serious environmental impacts. For example, dredging in the littoral waters would deepen the region locally and shift the front of the existing wave breaker zone landward, causing intensified wave action and erosion on the shoreline. This will exacerbate an already bad situation, possibly eroding away the entire barrier island and thus altering the existing barrier-lagoon regime and associated ecosystem. In light of such a prospect the Governmental agencies (Army Corps of Engineers) will not be inclined to issue a permit to dredge the shallow region. The field study consisted first of a seismic survey of the study area, conducted to record remotely the nature of the subsurface lithology. Sediment core samples were then collected at nine representative stations within the region off Kivalina.

These samples were collected using a vibra corer (Fig 3.2). The purpose of this later sampling was to obtain ground truth to interpret the subsurface seismic record. Since the exact location of the gravel was unknown, grab samples were first taken to determine the nature of the sea bed and to determine the feasibility of coring the subsurface. If the initial grab samples indicated a surface filled with cobbles and boulders, coring would be impossible in that region. Coring was possible in areas containing pebbles and muddy gravel.

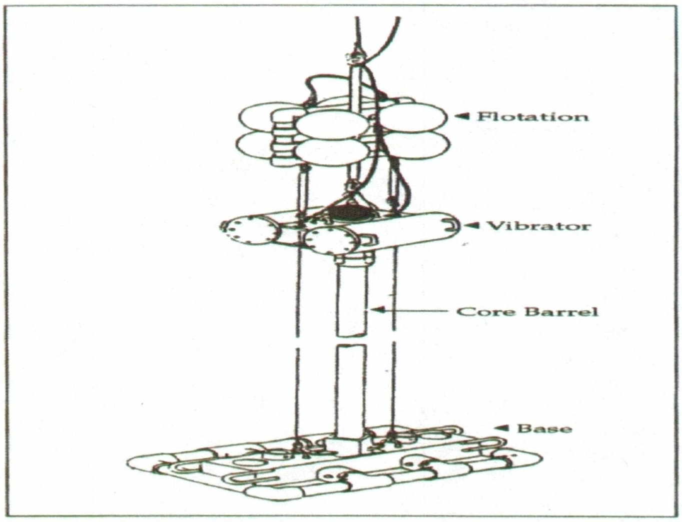


Figure 3.2 Schematic diagram of the vibra corer

The steps involved in the coring operation are graphically illustrated in Figs. 3.3- 3.6. The ship was anchored and the coring setup was deployed. The entire coring operation usually took about 20 minutes, depending on the hardness of the substrate. Coring was stopped when no penetration was achieved even after 2 minutes of operation. Grab samples were also taken at the coring location.

Figure 3.3 Deploying the vibra corer

Figure 3.4 Lowering the vibracorer with flotation device on top

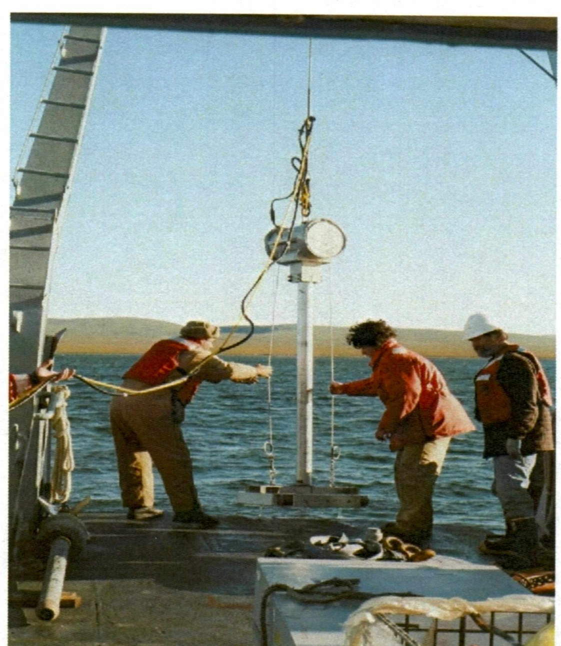


Figure 3.5 Raising the vibracorer after drilling

Figure 3.6 Laying the corer on the deck and removing the plastic liner

A total of 12 cores 28 grab samples were collected (Table. 3.1, Table. 3.2, and Fig. 3.7). Two of the cores were considered as composite samples, i.e., the core recovery was small and hence was sampled in bags. All the cores showed some gravel content. The maximum length of the cores was 1 m and the minimum was 25 cm. Two of the cores (27 & 28) were taken from the area near the Red Dog mine dock (Fig. 3.7). A seismic survey was also conducted in this area. Seismic reflection data were obtained from a total of five seismic transects, all of which were roughly parallel to the shoreline.

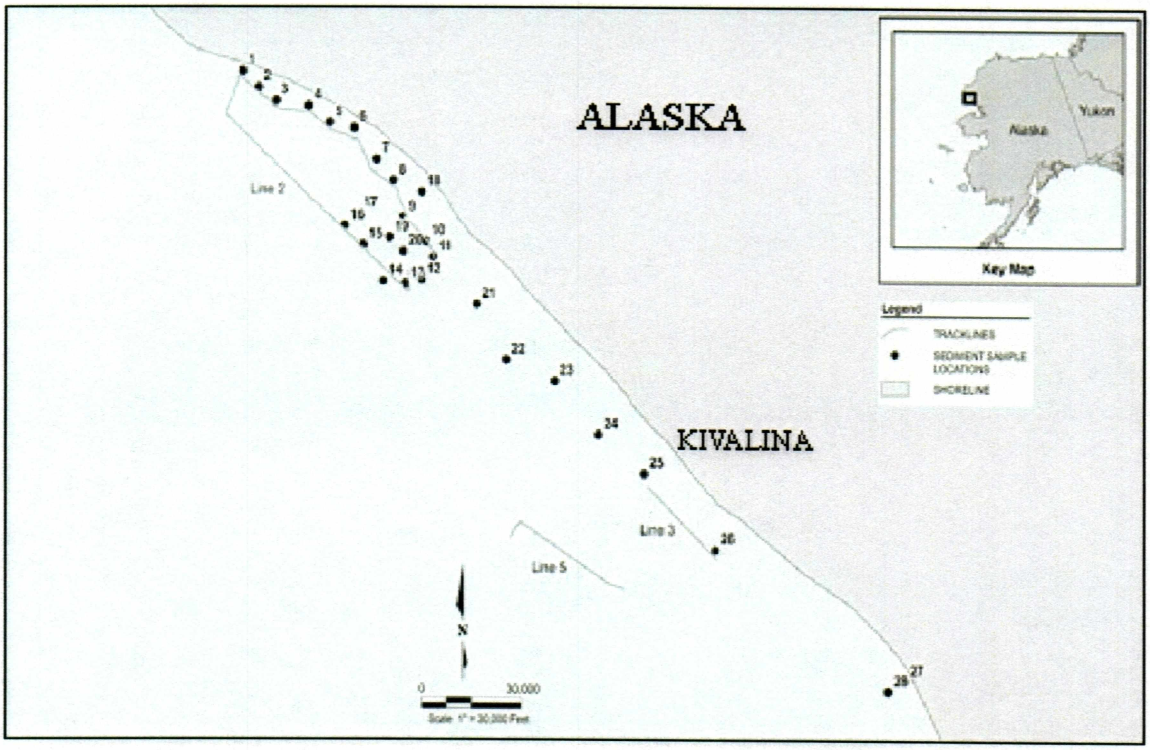


Figure 3.7 Location of sediment samples off Kivalina and vicinity

Table 3.1 Locations of sediment grab samples and depth at which collected

Station No.	Latitude °N	Longitude °W	Depth (m)
1	68.0531	165.444	9.50
2	68.0443	165.421	9.30
3	68.0363	165.389	11.1
4	68.0347	165.343	10.2
5	68.0257	165.312	11.3
6	68.0199	165.270	10.4
7	68.0067	165.249	11.1
8	67.5963	165.214	10.9
9	67.5814	165.197	10.5
10	67.5703	165.164	10.3
11	67.5574	165.150	11.0
12	67.5508	165.172	14.9
13	67.5457	165.196	18.6
14	67.5560	165.232	17.9
15	67.5654	165.262	17.7
16	67.5751	165.290	17.9
17	67.5827	165.270	15.7
18	67.5929	165.168	7.50
19	67.5675	165.222	14.5
20	67.5593	165.197	14.9
21	67.5353	165.095	13.7
22	67.5150	165.044	14.0
23	67.4958	164.572	13.0
24	67.4717	164.505	13.8
25	67.4478	164.436	12.8
26	67.4129	164.332	17.0
27	67.3441	164.049	7.50
28	67.3413	164.075	11.2

Table 3.2 Locations of the core samples off Kivalina

Station No.	Latitude °N	Longitude °W	Depth (m)
6	68.0199	165.270	10.4
9	67.5814	165.197	10.5
12	67.5508	165.172	14.9
13	67.5457	165.196	18.6
14	67.5560	165.232	17.9
15	67.5654	165.262	17.7
16	67.5751	165.290	17.9
17	67.5827	165.270	15.7
23	67.4958	164.572	13.0
26	67.4129	164.332	17.0
27	67.3441	164.049	7.50
28	67.3413	164.075	11.2

3.4 Laboratory Analysis

3.4.1 Grain size analysis

Each of the cores was first sliced longitudinally into equal halves using a circular saw. One half of each core was archived and the granulometric analysis was conducted on the other half using the sieve-pipette method (Folk, 1968) on 5-cm continuous core sections. The 5-cm sections were first wet sieved on a 200-mesh sieve. The -200 mesh slurry was then passed through a filter paper, dried, and the weight of the -200 fraction noted. The + 200-mesh (0.075 mm) fraction was dried, weighed and subjected to sieve analysis. The sieve analysis was conducted in accordance with ASTM standards for aggregate sieving. The gravel fraction was sieved into size fractions greater than 2 mm, 2.36 mm, 3.35 mm, 4.75 mm, 6.3 mm, 9.5 mm, 12.5 mm, 19 mm and in some cases up to 37.5 mm. The sand fraction was sieved into size fractions greater than 1.7 mm, 1.18 mm, 0.85 mm, 0.6 mm, 0.425 mm, 0.3 mm, 0.212 mm, 0.15 mm, 0.106 mm, and 0.075 mm. The weight of the

– 0.075 mm fraction, representing the fine material, was summed with the weight of the fine fraction obtained from wet sieving.

The following procedure briefly describes the pipette analysis for the fine fraction. To a representative sample from the -200 mesh fraction, water was added and the slurry was blended to disaggregate the particles. The slurry was poured into a cylinder for pipette analysis and diluted to 1000 ml total volume with distilled water. Two gm of sodium hexametaphospate was added to disperse particles before pipette analysis was conducted. Two 25 ml samples of the suspension were taken at appropriate time intervals and depths and the percentage of silt and clay was obtained. The data from the sieve and the pipette analyses were integrated and entered into Excel format and the weight percents of gravel, sand, silt, and clay were computed and tabulated.

3.5 Geological modeling

3.5.1 Introduction

Geological modeling of gravel deposits is still in its nascent stage and the technology used in modeling sand and gravel deposits is at least two decades old (Hack, 2002). Hence sand and gravel models are little studied and there have been no standardized rules of modeling. Bliss (1998), however, gives a general account of sand and gravel modeling and accordingly sand and gravel models can be classified into two types:

1. Descriptive models
2. Size models and other types of aggregate models
    a. Deposit size and geometry models

b. Particle size distribution within each model

c. Models of physical and chemical characteristics.

Bliss (1998) gives a detailed description of each of these models. For this investigation a size model was used to describe the gravel deposits. The first step was to compute basic statistics of the sample data followed by geostatistical analyses of the dataset. The geostatistical analysis led to a resource estimation which described the size of the deposit and also the volume of gravel at various cut-off grades. The particle size distribution was incorporated by plotting isopleth maps over the gravel distribution. Finally the physical and chemical characteristics were incorporated by conducting geotechnical analysis on the gravel samples.

3.5.2 Geostatistical analysis and resource estimation

3.5.2.1 Introduction

Geostatistics is the tool most often used by mining engineers to calculate ore reserves. It is based on the theory of regionalized variables developed by Matheron ((Journel and Huijbregts, 1978). Geostatistics encompasses three phases: structural analysis/variogram modeling , linear estimation/kriging and conditional simulation.

In the first phase the spatial continuity of the variable under study (which is partly random and partly deterministic) is described by a variogram. The variogram is defined as the mean of the square distance between pairs of data values. The experimental variogram curve consists of variogram values at increasing lag distances. Probabilistic models are then used to fit a theoretical distribution to the experimental values. These models give such parameters as range (the distance at which pairs of data values are uncorrelated), sill (the variance of the data values), and the magnitude of measurement error and small scale variability (nugget effect). The behaviour of the variogram in various directions can also be modeled with nested structures.

Once the variogram modeling is completed linear estimation methods are used to compute the value of the variable (grade) at unknown locations using known sample values. Ordinary kriging is the most common method of linear estimation as it is the best linear unbiased estimator. The kriging operation strives to minimize the estimation error at unknown locations and hence gives an indication of the variance of the grade at each sample value.

3.5.2.2 Resource estimation

Resource estimation using geostatistical analyses of gravel deposits are rare because of issues with the sampling biases, non-uniform sampling, the absence of the concept of Selective Mining Unit (SMU) in gravel mining and the usage of additive variables during the spatial analysis (Hack, 2004). One of the first investigations of the use of geostatistical techniques was in modeling the thickness of gravel deposits and its effect on gravel reserves (Royle and Hosgit, 1974). The use of non-parametric geostatistical techniques (Magalhaes and Ribero, 1999) for the identification of aggregate deposits in the OCS of Spain was one of a few papers published in the area of marine mining. The work done by Arthur (1994) is a significant milestone in applying geostatistical techniques for unconsolidated deposits. He demonstrated the efficacy of variogram modeling of thickness values of gravel deposits, but the variogram modeling of size grading data did not produce satisfactory results due to poor sampling methods and due to the high micro variation associated with gravel deposits. Thus sizing data can be highly erratic and biased and previous investigations have failed to produce satisfactory results.

Local and global estimations of grades and volumes are often insufficient at the mine planning stage as they do not convey the dispersion characteristics of a deposit (Journel and Huijbregts, 1978). This is especially true in the case of base and precious metal deposits where ore grades vary erratically. Conditional simulation techniques such as Turning Bands and Sequential Gaussian techniques, are now being routinely used in the mining industry as a supplement to geostatistical techniques in order to minimize the risk associated with the classical techniques. However no literature exists about their application in the resource estimation of sand and gravel deposits.

Geostatistical analysis and resource estimation was conducted using the software package ISATIS. The steps consisted of the following:

1. Convert the latitude and longitude into northing and easting respectively.
2. Construct a grid to cover the length and breadth of the study area.
3. Compute basic statistics and a histogram of gravel values.

4. Do a quick estimation using the Inverse Distance Weighting method.
5. Compute an experimental variogram by using the best value of lag and tolerances to produce a smooth variogram.
6. Fit a variogram model to the experimental variogram by trial and error.
7. Perform various kriging analyses using the variogram model.
8. Perform cross-validation to choose the best kriging technique based on error statistics.
9. Produce a gravel map for the study area.
10. Plot the grade tonnage curves and calculate tonnage.

3.6 Geotechnical analysis

The intended use of the OCS gravel is for foundation fill. The main requirement for gravel as a fill material is the absence of fines (< No. 200 mesh). If a fill material contains fines more than 8 % it is frost susceptible and can cause surface heave upon freezing (Barksdale, 1991).

One of the key components of aggregate base course (fill) is the compaction of the sediments. The fill mixture must be thoroughly compacted for its potential load bearing capacity to be fully mobilized. The determination of the unit weight of soil or graded aggregate in a standard condition of compaction is an essential element of construction control specifications (Highway materials engineering, 1990). Either the *standard Proctor* or the *modified Proctor* density tests are used in the laboratory to establish a standard reference density. The standard and modified Proctor tests are designed to produce a well-defined, moisture-density relationship curve that gives optimum moisture content corresponding to the maximum dry density obtained using a specific compactive effort (Barksdale, 1991).

The other important strength parameter tested was the California Bearing Ratio (CBR) test. The CBR is frequently used to characterize the strength of aggregate fill material. An increase in the CBR value indicates an increase in strength. The laboratory compacted CBR values of the materials to be used as fill material should not be less than 100 after curing and four days of soaking. Test specimens shall be compacted at optimum moisture by the *modified proctor* (Barksdale, 1991).

Chapter 4
RESULTS AND DISCUSSIONS

4.1 Results of the geophysical study

4.1.1 Geophysical data

As a result of the acoustic noise generated by the sea conditions, and the signal to noise ratio, the quality of the overall data on seismic reflection was often poor. Due to adverse sea conditions, it was not possible to run transects along the originally planned lines or to obtain data on an organized grid. This would have improved the overall mapping of the coarse grained sediment.

The data were interpreted using the principle of seismic facies analysis. This method identifies various reflection patterns (uniform horizontal reflectors, discontinuous, chaotic reflectors, high amplitude reflections, etc.) on the graphic records and then assumes they are characteristic of a particular lithology or depositional environment. For example, a geophysical facies or stratigraphic unit on the record that is comprised of continuous, interbedded thin layers suggests the presence of fine-grained sediment (Figure 4.1). Coarse-grained deposits, such as cobbles and gravels, usually produce high amplitude reflections (dark patterns and small diffractions on the records). These can be discontinuous and often demonstrate multiple reflections (Figure 4.1). Hyperbolic reflectors are often indicative of the presence of boulders that may be in a till deposit or ice rafted diamicton with drop stones.

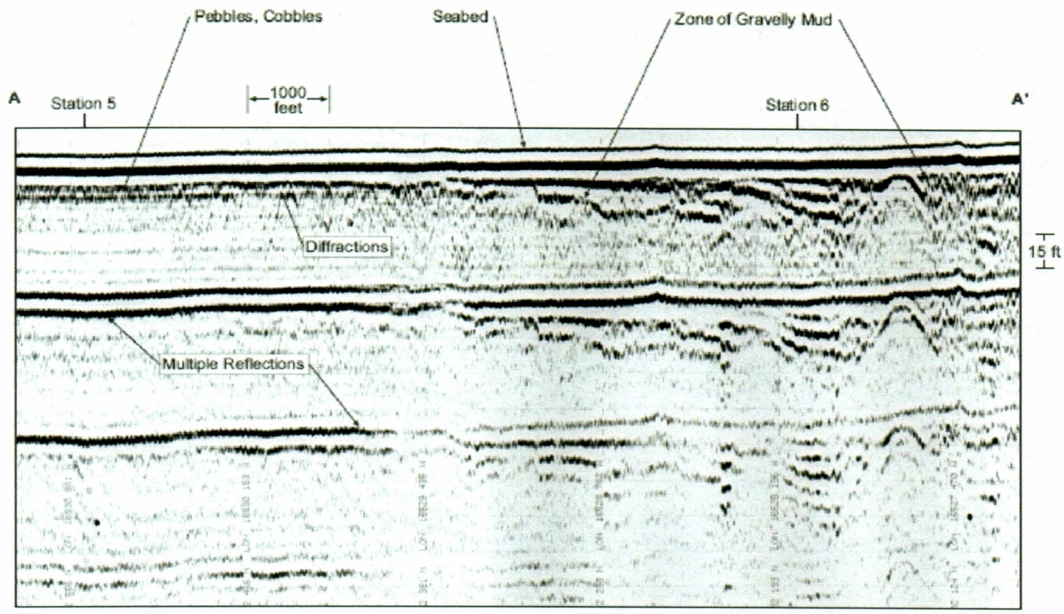


Figure 4.1 Example of a seismic record indicating distinct zones of gravel in the Kivalina area

4.1.2 Interpretation of the geophysical record

After a general classification of the sediment characteristics observed on the profiles the next step was to interpret these seismic facies in terms of the lithology or geological structures. The availability of sediment grab samples in conjunction with vibracore lithostratigraphic data makes the interpretation of the seismic record considerably easier and more reliable.

Based on the geophysical data and the information from the surface and vibracore samples two zones of muddy gravel were mapped. These two zones are located offshore of Kivalina Lagoon and just south of where Kisimilok Creek flows into the ocean (Figure 4.2)

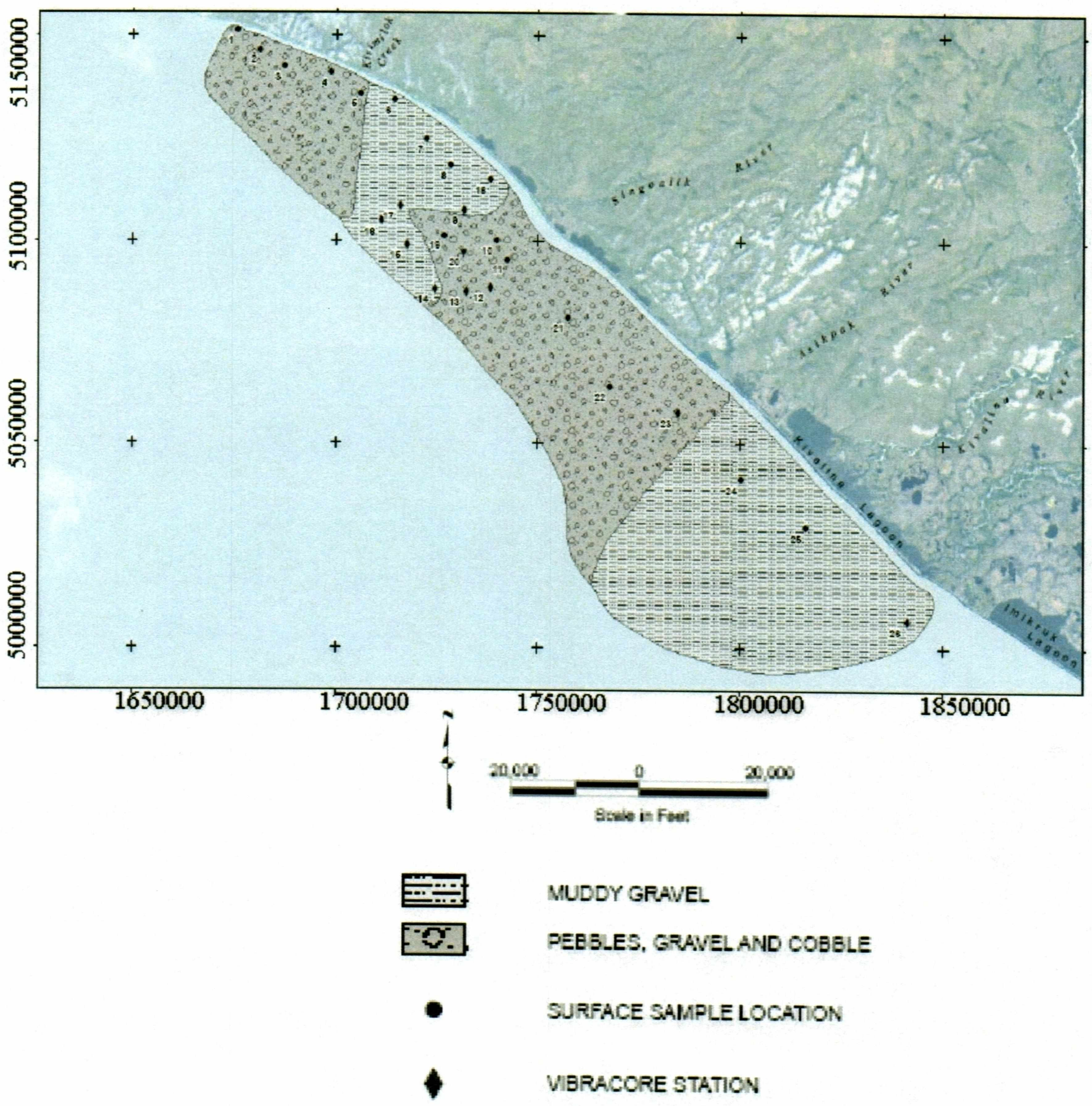


Figure 4.2 Geologic map of the Kivalina area from grab samples and geophysical data

On the seismic reflection records these muddy gravel deposits are characterized by good subsurface penetration (over 25 m) with no evidence of multiple reflections (Figure 4.1).

Subsurface penetration was limited to approximately 9 m below the sea bed in the muddy gravel zone farthest north (Figure 4.3). On the seismic bottom profiler records subsurface penetration in these two zones was limited to less than 1.5 m which is indicative of the presence of some coarse grained material. The presence of coarse-grained material, gravels and cobbles were identified and mapped in two zones. These zones correlate with the massive rock outcrops that can be observed on shore (Figure 4.2). The seismic reflection data in these areas showed little or no penetration and several multiple reflections indicative of a very hard substrate (Figure 4.3). The sediment samples were used as ground truth to classify this acoustically hard material as cobbles and pebbles.

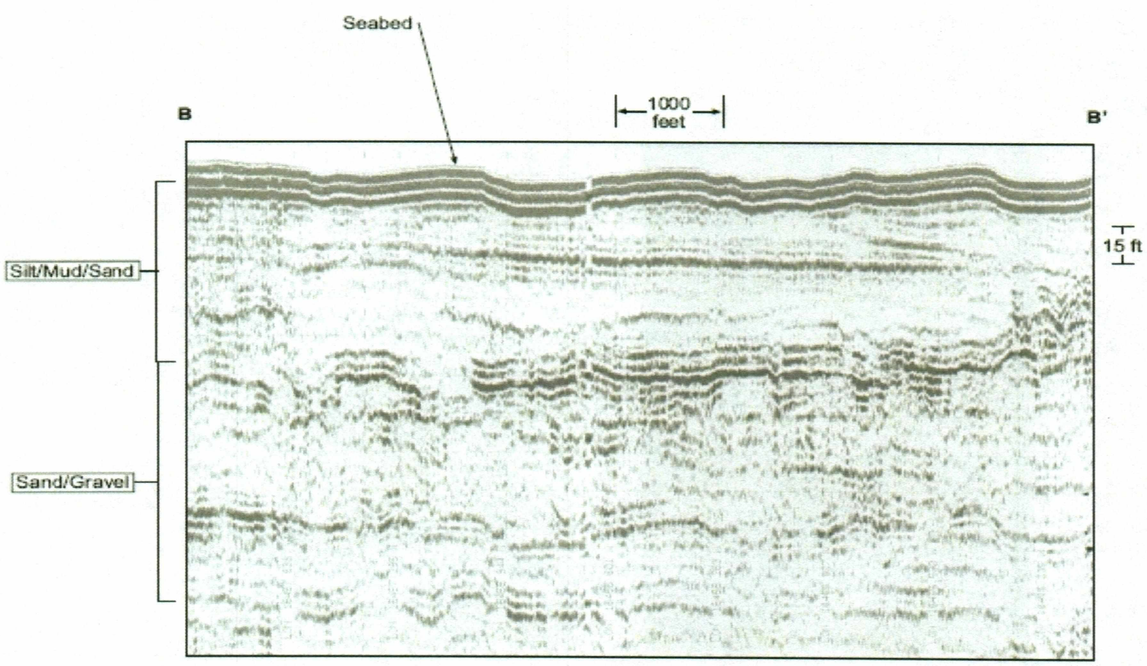


Figure 4.3 Example of seismic record indicating coarse grained sediments

4.2 Results of the geological study

The investigations at Cape Thompson-Kivalina revealed a significant amount of gravel, which was further analyzed. The database consisted of 28 grab samples and 9 core samples. Generally the lithostratigraphy of the cores consisted predominantly of sand for the top 10 cm of the core and then consisted of gravel to the bottom of the core (Appendix A, Appendix B). The 2.36 to 3.35 mm size fraction dominated most of the cores in the north of the study area. The gravel, greater than 19 mm size fraction, was prominent at the base of the core due to cobble size particles at the base. The maximum length of the cores was 1 m. It can be seen from the figures (Appendix B) that at the bottom of most of the cores the gravel percentage was higher than in the rest of the core. As the particle size increased at the core bottom further penetration was precluded. Modeling the vertical section of the substrate with just nine cores would not provide any statistically reliable analysis and hence the vertical variation in gravel was not further analyzed.

However the preliminary map does not provide any data on the actual percentages, and the particle size distribution of the gravel deposit. The database was augmented by grab sample data obtained from previous investigations in the Chukchi Sea from 1953-1965 (McManus and Creager, 1965; Roberts, 1976). The next step was to model the size, geometry, and the particle size distribution of the gravel deposit using the grab sample data from the combined data set.

4.3 Exploratory data analysis

The data from previous investigations contained information of the percentages of gravel, sand, mud as well as sedimentological parameters such as mean, sorting and skewness of the sediments. The cumulative percentages above 16 mm, 8 mm, 4 mm, were also entered into the current database. The gravel values represent the percentage of gravel in the dry weight of the samples. This gravel value represents the grade in our estimation process.

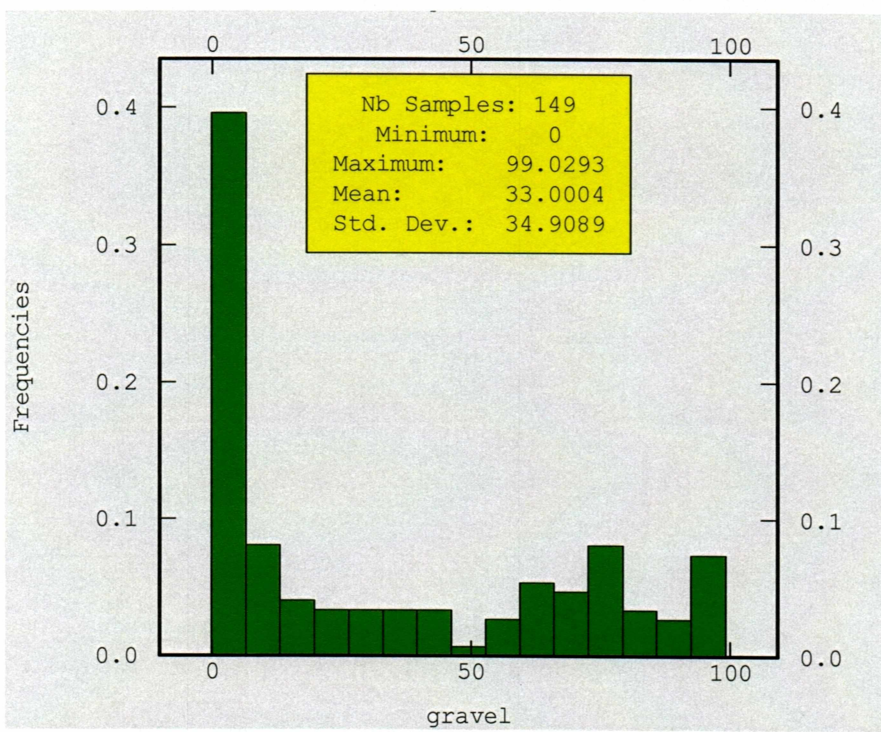
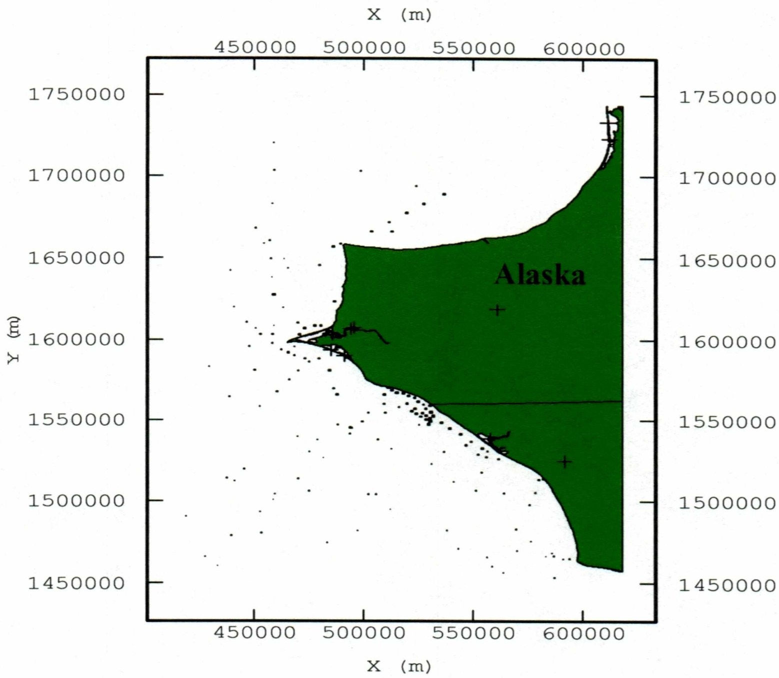


Figure 4.4 Histogram and summary statistics of gravel values for the combined dataset.

As can be seen from Fig. 4.4 the histogram for gravel values more or less resembles a uniform distribution if we ignore the large percentage (around 40%) of low values (0-

5%). However the paucity of percentages of high values could affect the estimation process as discussed later in the chapter.



Scale: 1cm = 40km

Figure 4.5 Base map of the study area showing grab sample locations

Fig. 4.5 shows the base map of the study area. The high gravel values are shown with large symbols. From the base map it is clear that the high values follow the coastline very well and as we move away from the coastline the gravel percentage decreases.

Figures 4.6 to 4.8 show scatter plots of percentage gravel versus the mean size of sediments, sorting of sediments and water depth respectively. The mean size of the sediments is a sedimentological parameter and is the average of the 16th, 50th, and 84th percentile of weight retained. Scatter plots are good means to identify meaningful relationships between variables of interest, which can be further analyzed during the estimation process. The mean size of the sediments shows a good correlation with gravel percentage, and it increases exponentially with increase in gravel percentage. This trend can be utilized in future exploration for gravel in the area. The other two scatter plots do not show significant correlation between the variables but the sorting and water depth do show a decrease with increase in gravel percentage. The higher gravel percentage at shallower water depths is further evidence of gravel being present near the coastlines.

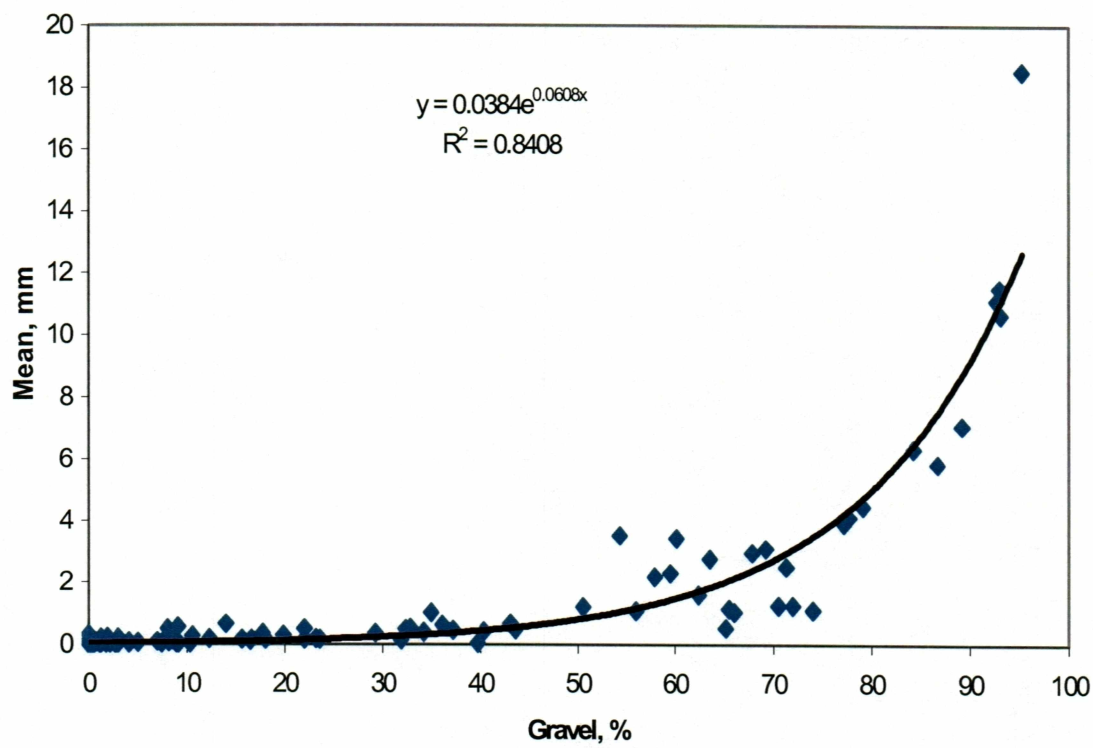


Figure 4.6 Scatter plots of percentage gravel versus mean size of sediments

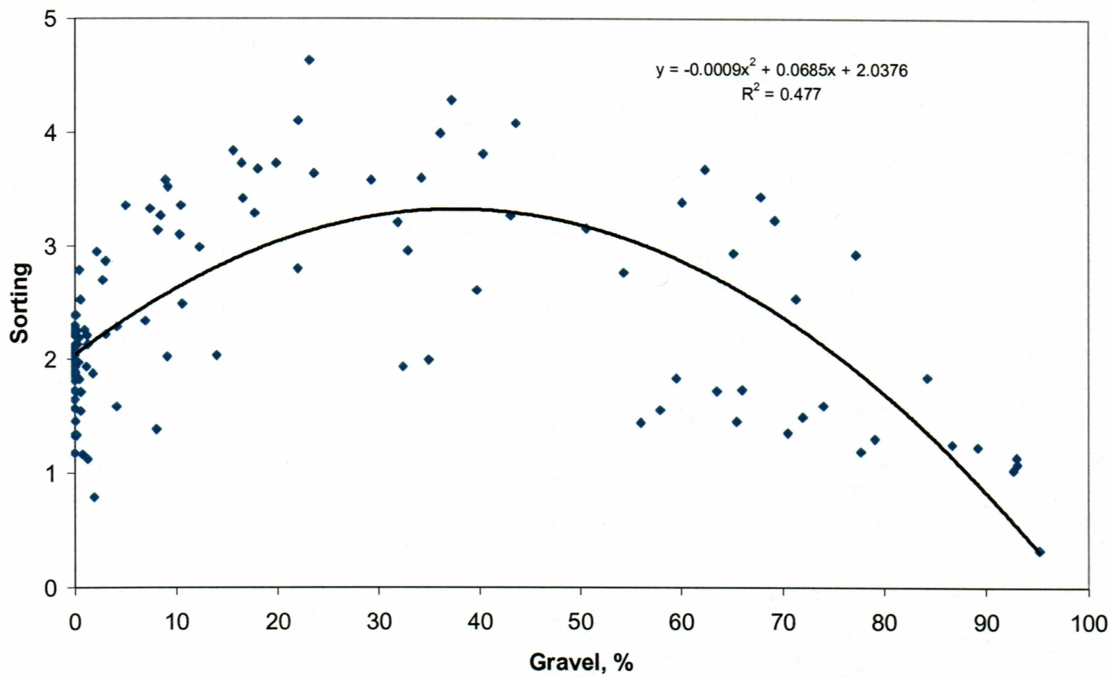


Figure 4.7 Scatter plots of percentage gravel versus sorting of sediments

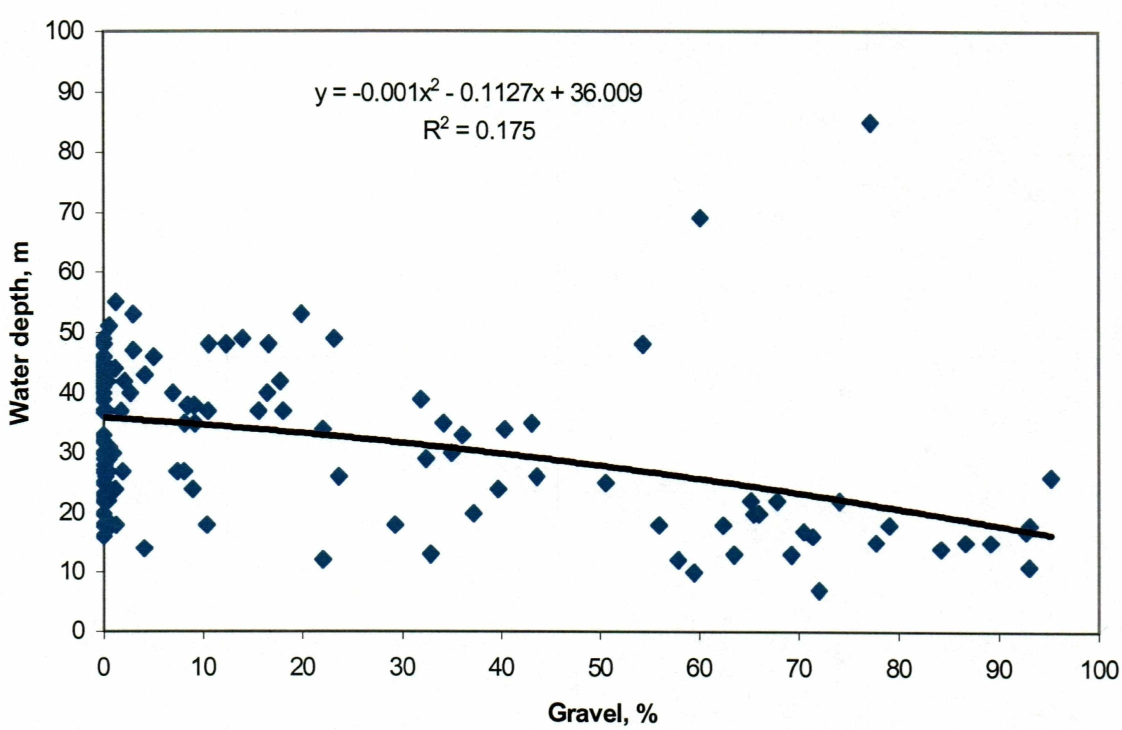


Figure 4.8 Scatter plots of percentage gravel versus water depth

4.4 Variogram modeling and cross validation

Figure 4.9 shows the omnidirectional variogram curve plotted for gravel values for the Kivalina study. The green dots indicate the variogram values at lag values of approximately 12000 m and the numbers indicate the number of pairs of values at each lag. The dotted line is the sill and dark red line is the variogram model fitted to the experimental values. A single variogram model did not fit the data and hence multiple variogram models were fitted to the experimental variogram values.

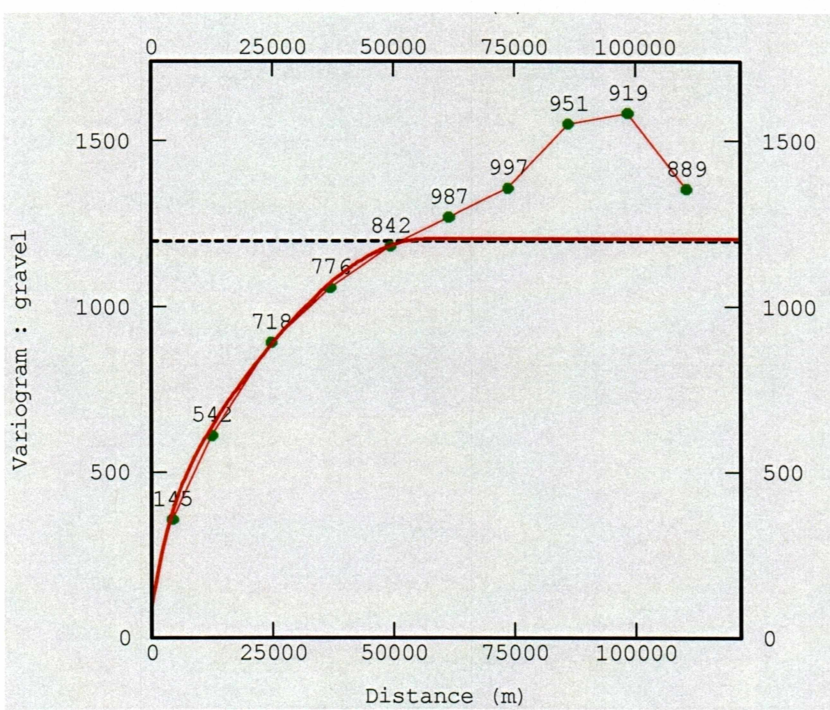


Figure 4.9 Variogram curve for gravel values for the Kivalina study.

The parameters of the compound variogram model are:

$$\gamma(h) = C_0 + C_1\left(\frac{3h}{2a_1} - \frac{1h^3}{2a_1^{\ 3}}\right) + C_2\left[1 - \exp(-h/a_2)\right] \quad \text{(for } 0 < h < a_1\text{)}$$

$$= C_0 + C_1 + C_2\left[1 - \exp(-h/a_2)\right] \quad \text{(for } 0 < h < a_2\text{)}$$

$$= C_0 + C_1 + C_2 \quad \text{(for } h > a_2\text{)}$$

Where C_0 is the Nugget part of the model with a value of 85.79.

C_1 and a_1 are the sill and range of the spherical model with values of 300 and 12000m respectively.

C_2 and a_2 are the sill and range of the exponential model with values of 815 and 57000m respectively.

The omnidirectional variogram model fits the data very well. Anisotropy in the data was also checked for and the data did show anisotropy in the N 50 E /N 40 W direction. It also displayed a high nugget variance and the variogram models failed to fit the data well. This evidence of anisotropy might prove useful in future sampling design in the area.

After fitting the variogram model to the data Ordinary Kriging (OK), Simple Kriging (SK), and Ordinary Kriging with anisotropy was performed and cross validation experiment was conducted to determine the best kriging technique for reserve estimation and final gravel distribution maps. Table 4.1 shows the summary of the error statistics for the cross validation study for the three kriging methods.

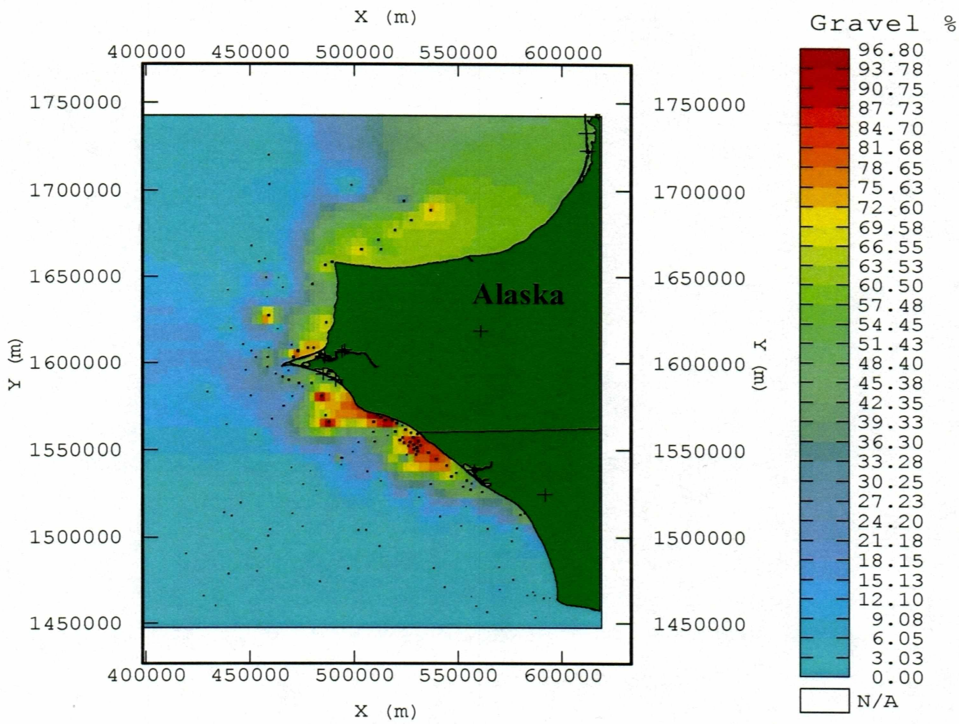
Table 4.1 Results of cross validation study

	Ordinary Kriging	Simple Kriging	Ordinary Kriging with anisotropy
Mean Prediction error	1.02	2.03	2.11
Root Mean Square error	20.08	20.15	21.25
Average Standard error	21.3	21.25	25.92
Mean Standardized	0.03	0.06	0.05
R Square	0.68	0.67	0.64

From the table it can be observed that though the R^2 value is quite similar for the three techniques, the mean prediction error, the RMS error, the average standard error and the mean standardized are less for OK than for the other two techniques. The average standard error, which represents the kriging standard deviation at the sample locations, is quite high even for OK.

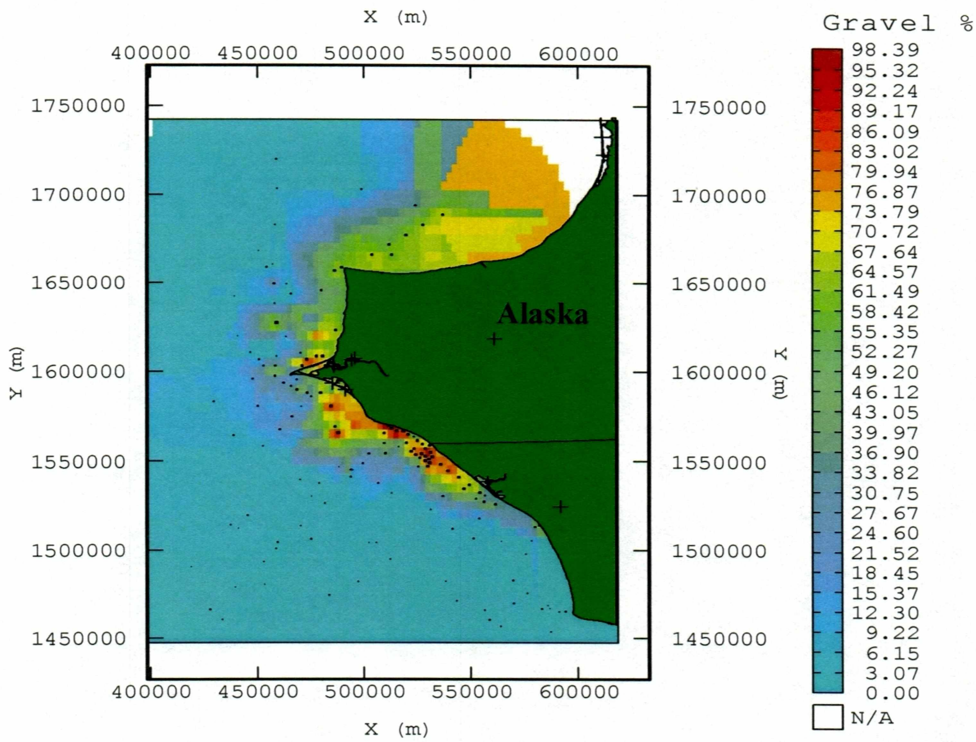
4.5 Gravel distribution maps

The gravel distribution maps for the Kivalina region and vicinity were produced using Inverse Distance Weighting (IDW) and Ordinary Kriging (OK) and they are shown in Figures 4.10 and 4.11. The basic premise of IDW is that data points are weighted by the inverse of the distance to the estimation point. It is observed from the figure that OK produces a smoother map than IDW. Kriging was done using point variables rather than on a block as the concept of Selective Mining Unit (SMU) is not common in gravel mining and morever SMU in a marine mining situation does not make any practical sense.



Scale: 1cm = 40km

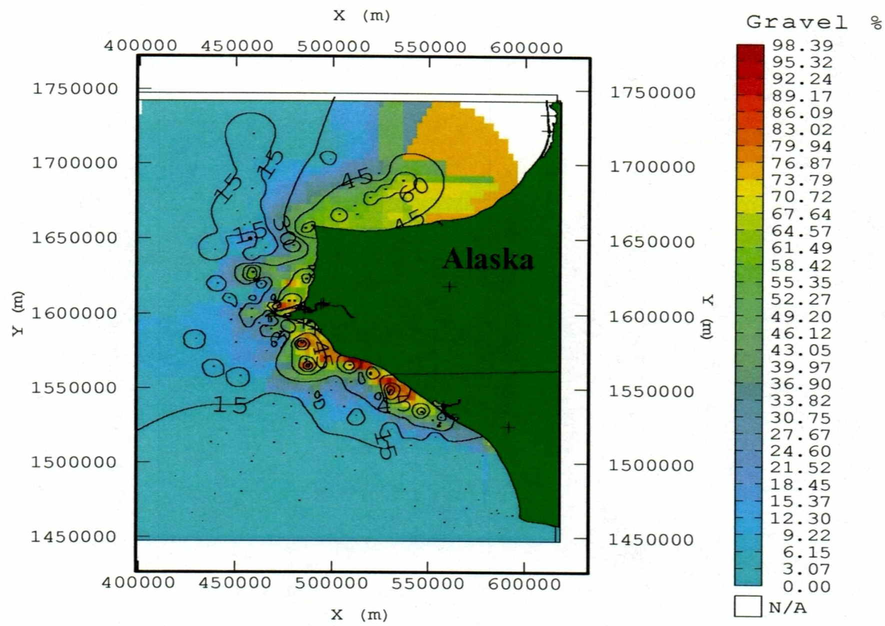
Figure 4.10 Gravel distribution map for the Kivalina area using the Inverse Distance Weighting method



Scale: 1cm = 40 km

Figure 4.11 Gravel distribution map for the Kivalina area using Ordinary Kriging

Figures 4.12 to 4.14 show the gravel distribution maps with cumulative percentage values at various cut-offs superimposed on them. The contours showing cumulative percent values are higher near the coast and decrease as one moves further offshore. One possible explanation for this is that the glacial meltwater only carried finer sediments offshore while the coarser particles remained near the shore. Thus this type of deposition is evidence of a glacial origin for the gravel.



Scale: 1cm = 40km

Figure 4.12 Isopleths of >2 mm and < 4 mm size fractions

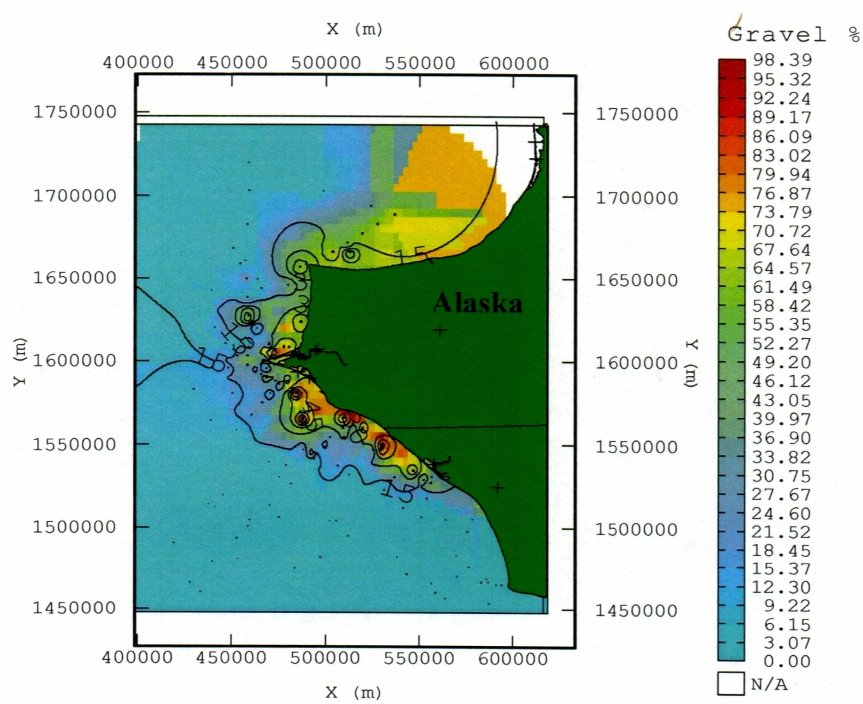


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Figure 4.13 Isopleths of > 4 mm and < 8 mm size fraction

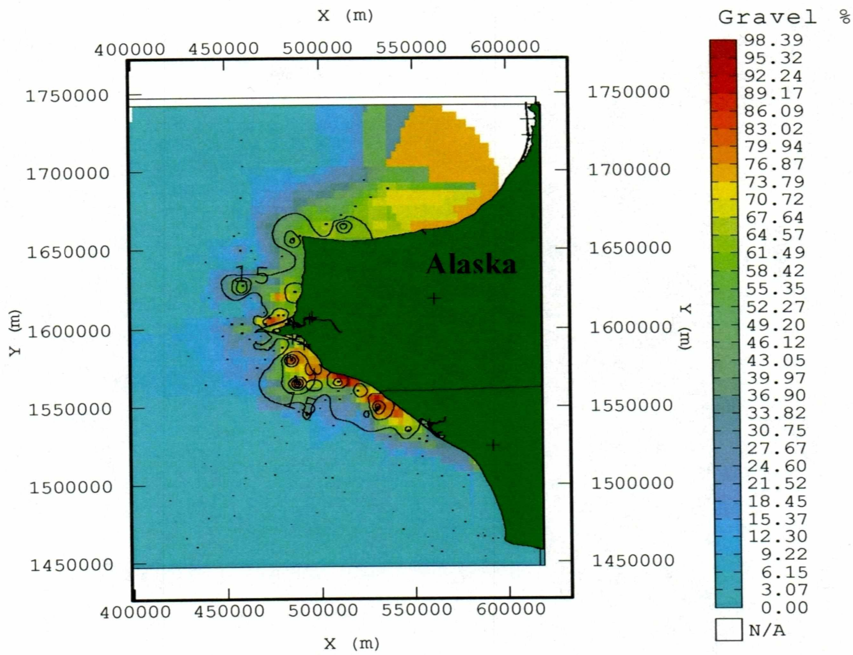

Figure **Scale: 1cm = 40km** **4.14 Isopleths of > 8 mm size fraction**

4.6 Simulations

Two types of simulation techniques were employed to produce distribution maps and volume calculations: The Turning Bands method and the Sequential Gaussian method. Each method requires a standard normal transformation (Gaussian Anamorphosis) of the data. Figure 4.15 shows the histogram of the transformed data. The mean of the transformed values is 0 and the standard deviation is 1, thus confirming the normality of the data.

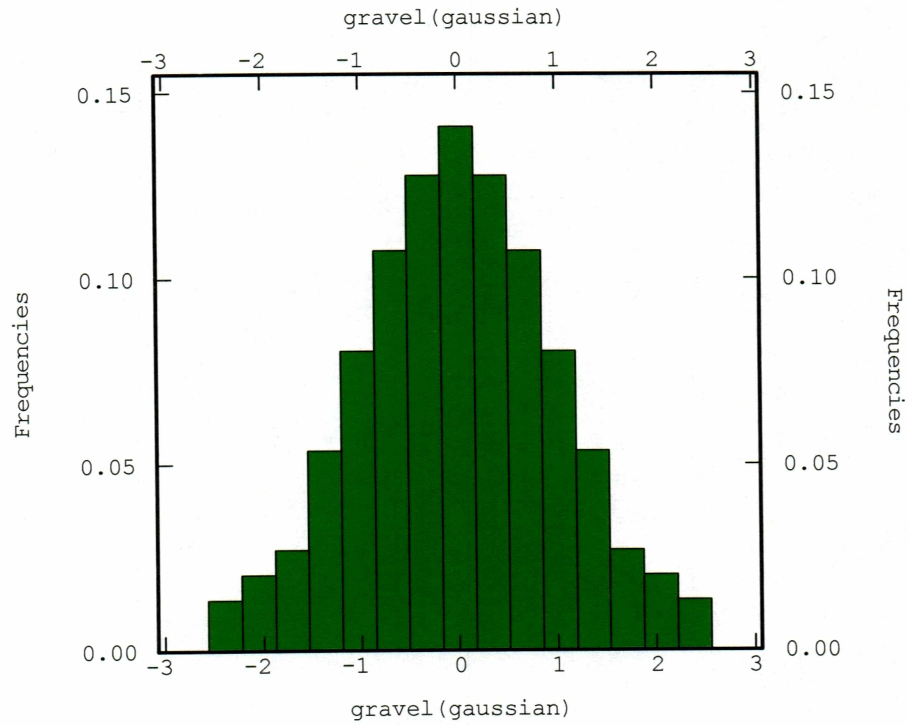

Figure 4.15 Histogram of the transformed data

Figures 4.16 and 4.17 show the gravel distribution maps for the Sequential Gaussian and the Turning Bands simulations respectively. Both the simulations follow the estimation near the coastline pretty well, though both the techniques overestimate the higher values (see legend). The Sequential Gaussian simulation overestimates the gravel than the other methods. This will be quite evident in the next section.

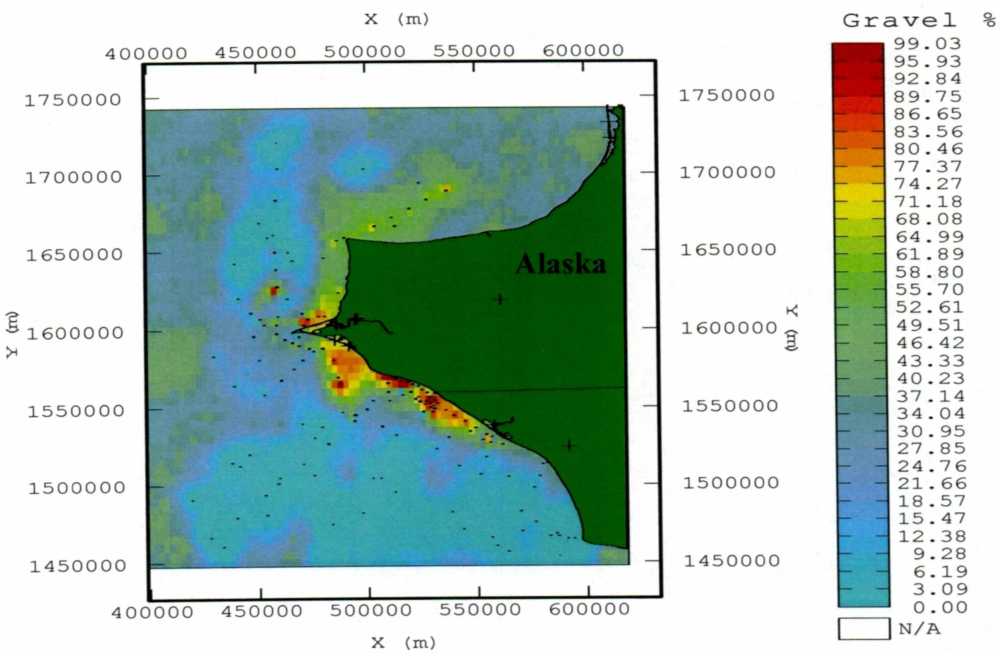

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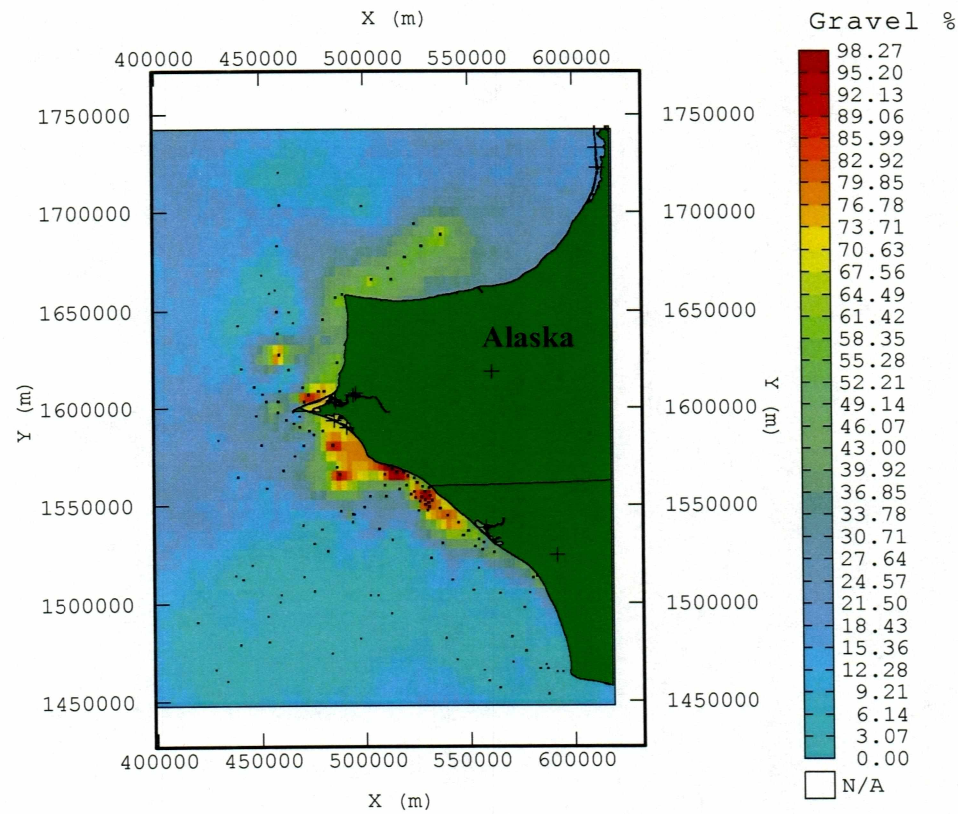
Figure 4.16 Gravel distribution map using sequential Gaussian simulation



Scale: 1cm = 40km

Figure 4.17 Gravel distribution map using the Turning Bands simulation

4.7 Grade –tonnage

This was the most important aspect of the investigation. The three parameters computed were the cut-off grade, the mean grade and the volume of gravel in m^3. The grade of gravel is defined as the percentage gravel at a location. The cut-off grade is defined as the cut-offs at various gravel percentages, in this case ranging from zero to hundred. These parameters were computed for four methods: IDW, OK, Turning Bands (TB) and Sequential Gaussian (SG). The values are summarized in Tables 4.2 and 4.3 respectively.

Table 4.2 Gravel volumes for the four estimation techniques at various cut-off grades.

Cutoff	IDW volume (m^3)	Kriging volume (m^3)	SG volume (m^3)	TB volume (m^3)
0	4,247,738,000.00	3,792,680,000.00	5,281,365,200.00	4,347,144,800.00
10	3,970,738,800.00	3,481,040,000.00	5,054,461,600.00	4,007,414,800.00
20	3,556,194,000.00	3,239,360,000.00	4,676,296,000.00	3,383,096,000.00
30	3,328,378,800.00	3,010,400,000.00	3,898,616,400.00	2,854,622,400.00
40	3,045,210,400.00	2,700,880,000.00	1,790,000,800.00	2,434,862,400.00
50	2,638,764,000.00	2,395,600,000.00	1,087,856,800.00	1,773,401,200.00
60	1,311,707,600.00	1,666,320,000.00	650,776,400.00	764,111,600.00
70	442,104,800.00	775,920,000.00	434,748,400.00	454,082,800.00
80	204,452,800.00	150,520,000.00	188,743,600.00	202,226,800.00
90	43,290,400.00	22,175,200.00	61,501,200.00	55,332,000.00

Table 4.3 Mean gravel grades for the four estimation techniques at various cut-off grades.

	Mean Grade, %			
Cutoff	IDW	OK	SG	TB
0	20.04	17.79	24.91	20.51
10	40.18	44.22	33.71	33.15
20	51.08	52.01	37.52	43.84
30	55.34	56.75	41.43	51.29
40	58.50	61.32	54.28	55.83
50	61.48	64.30	64.94	61.08
60	67.73	69.39	74.59	72.63
70	79.18	75.17	80.38	79.65
80	85.74	84.56	87.71	86.02
90	93.04	93.41	96.14	94.14

The results are plotted in Figure 4.18 and Figure 4.19 respectively. From Fig. 4.18 it is observed that for the weighted average techniques IDW overestimates at 0 % cutoff, but it falls below the OK curve at about 60 % cut-off. Of the simulation techniques the SG overestimates the most at the beginning but rapidly falls off below the three curves at 40 % cut-off and joins them again at the end. In other words the SG method overestimates at lower gravel cut-offs, but this is insignificant as gravel will only be mined at above 85 % cut-off due to the large amount of fines at lower cut-offs. The mean grade for the two weighted average techniques are quite similar at about 40 % cut-off at which point the IDW curve falls below the OK curve and again joins it at about 70 % (Fig. 4.19). The SG method again overestimates the mean grade at the beginning but joins the other three curves at about 70 % cut-off. All of the four curves are almost parallel from 70 % cut-off onwards, i.e., all the four methods have the similar mean grades from 60 % cut-off onwards.

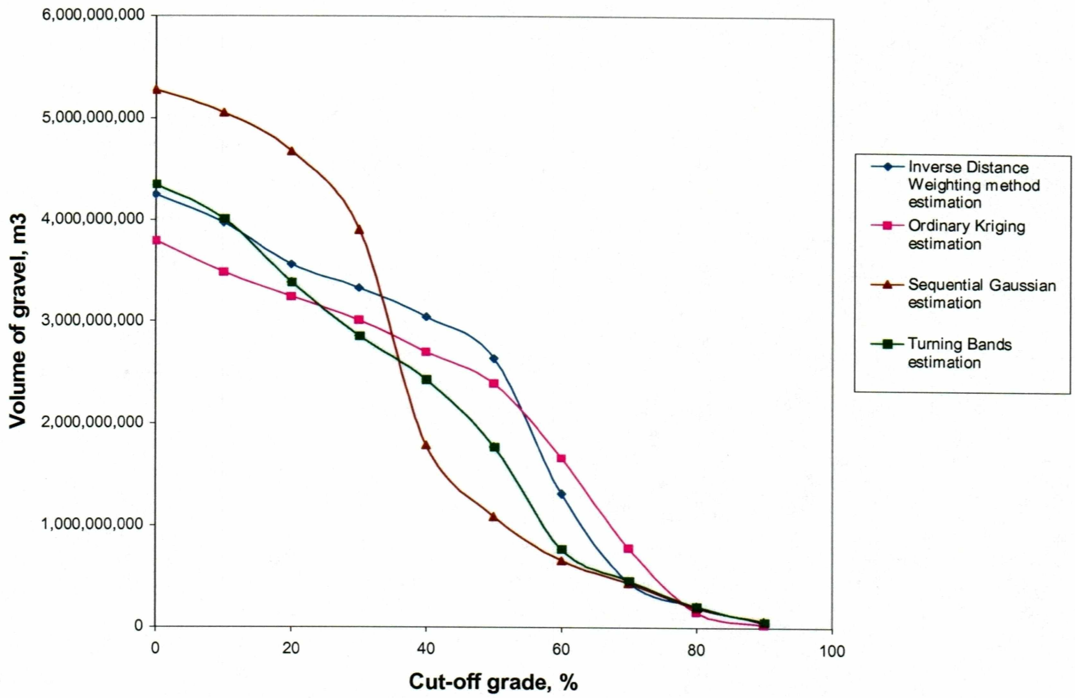


Figure 4.18 Grade-volume curves for gravel for four estimation techniques

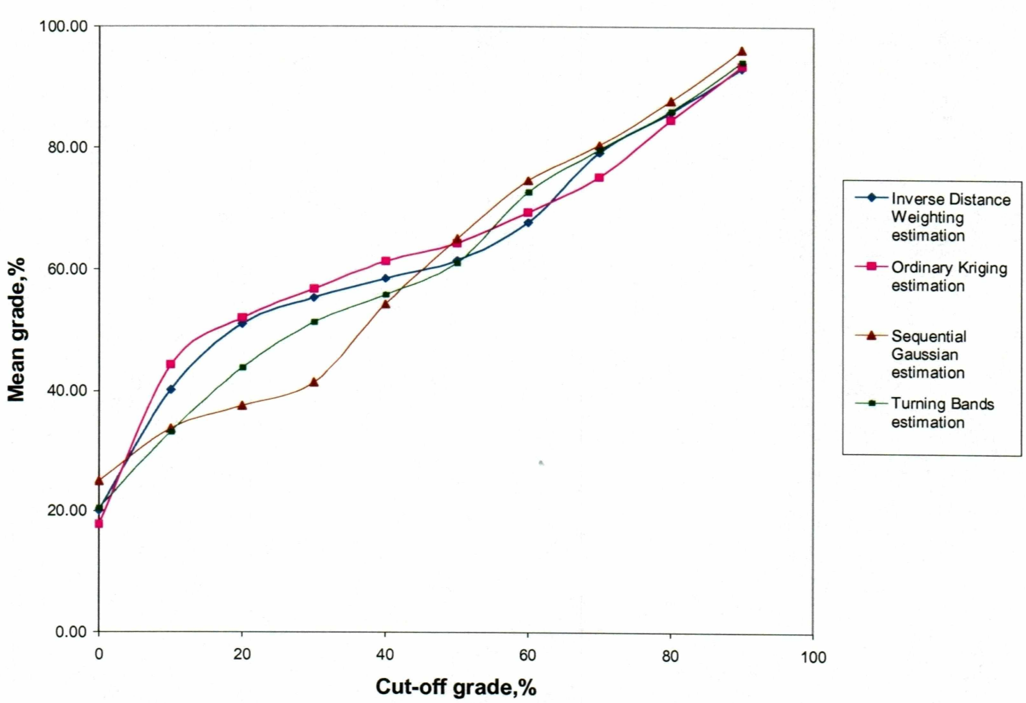


Figure 4.19 Mean gravel grade at various cut-offs for the four estimation methods

4.8 Geotechnical analysis

The geotechnical analysis was subcontracted to Shannon and Wilson, Inc., Fairbanks. The two tests conducted were the moisture density test (ASTM D 1557) and the California Bearing Ratio (CBR) (ASTM D 1883). The moisture density tests provides values for optimum moisture content for different compactive efforts (Figure 4.20). From the figure the optimum value of moisture is 3.8 % for a compactive effort of 4.5 kg and 4.9 % for a compactive effort of 2.5 kg. The CBR test gave a CBR value of 92 for the standard blow of 56 which is the last point in the curve (Figure 4.21). A CBR value of 80-100 indicates good material for foundation fill. The detail graphs and tables for the geotechnical analysis are given in the Appendix C.

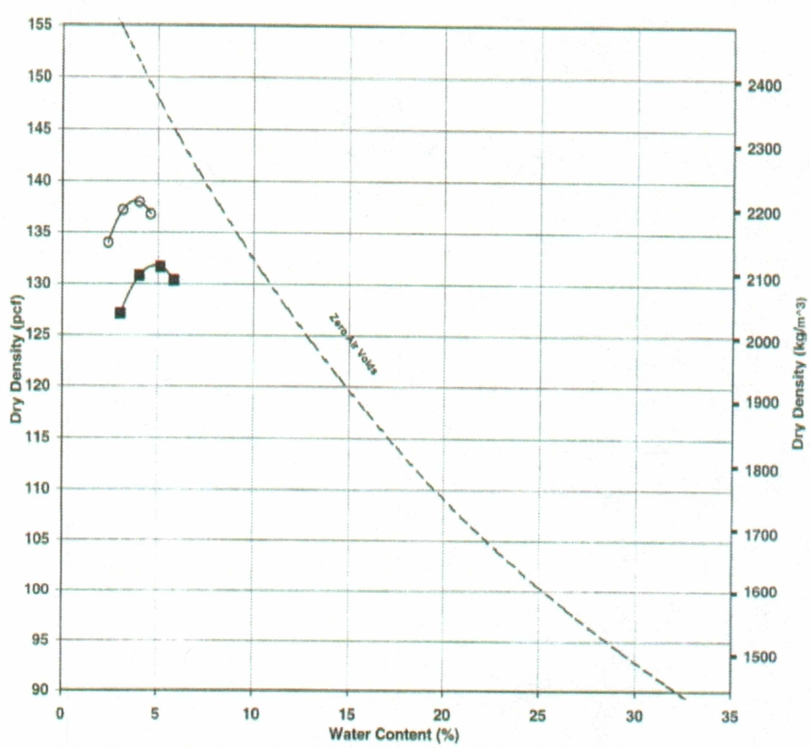


Figure 4.20 Results of the moisture density test

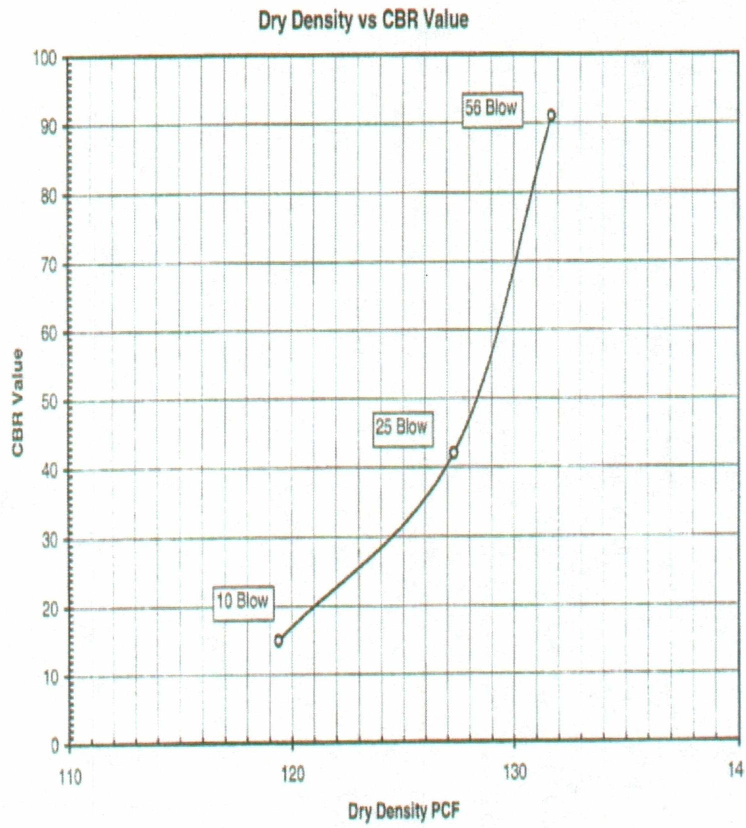


Figure 4.21 Results of the California Bearing Ratio test

4.9 Discussion

The first hypothesis tested was that the nearshore region off Kivalina would contain sufficient gravel for the relocation plan of the village of Kivalina. The statistical analysis seems to validate this hypothesis. The relocation plan would need at least 100×10^6 m^3 of gravel and the investigation suggests at least 20×10^6 m^3 of gravel above 90 % cut-off and at most 60×10^6 m^3 of gravel above 90 % cut-off is present in the inner shelf off Kivalina. However if 80 % cut-off is chosen, then the estimated volume of gravel present in the nearshore exceeds 100×10^6 m^3 of gravel. The overestimation in gravel volumes by the simulation methods is probably due to the high percentage of low values in the original data.

The second hypothesis for the investigation was that the presence of gravel in the Kivalina inshore area can be attributed to the regional Pleistocene glaciation history (Figs. 4.22 and 4.23). The results of the study seem to validate this hypothesis. In the study area, glaciers during the Wisconsin and the Illinoian ice ages transported gravel from the nearby DeLong Mountain Range. The terminal moraine gravely outwash associated with the glaciers was likely to have deposited in the present day nearshore. It is to be expected that the lag gravel deposits would occur close to or at the seafloor surface provided they are not blanketed by thick finer sediments. It is suggested, by implication, that paleo gravel lag deposits will not occur in nearshore areas which were not exposed to Pleistocene glaciation. This is consistent with earlier investigations in the Shishmaref area located due south of Kivalina. The Shishmaref nearshore region, which was not glaciated during the Pleistocene, has no gravel in the surficial sediments (Bandopadhyay et al, 2004). Presumably, the presence of intense currents off Kivalina has prevented deposition of thick contemporary fine deposits over the lag gravels.

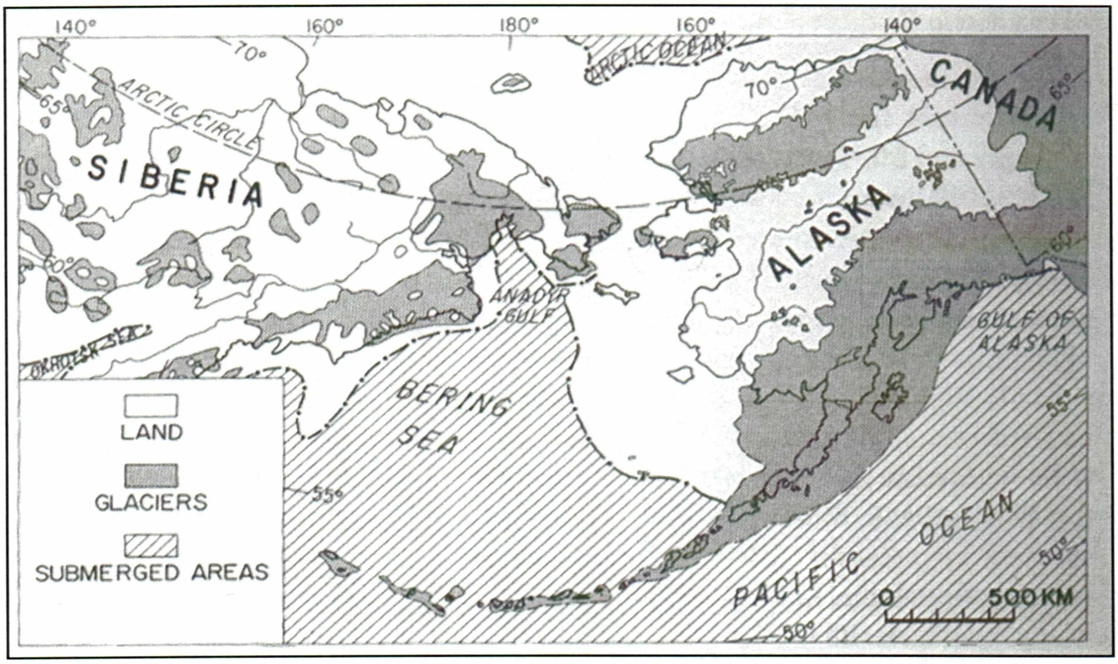


Figure 4.22 Paleogeography of Beringia during the height of the Wisconsin or Wurn glaciation (After Hopkins, 1982)

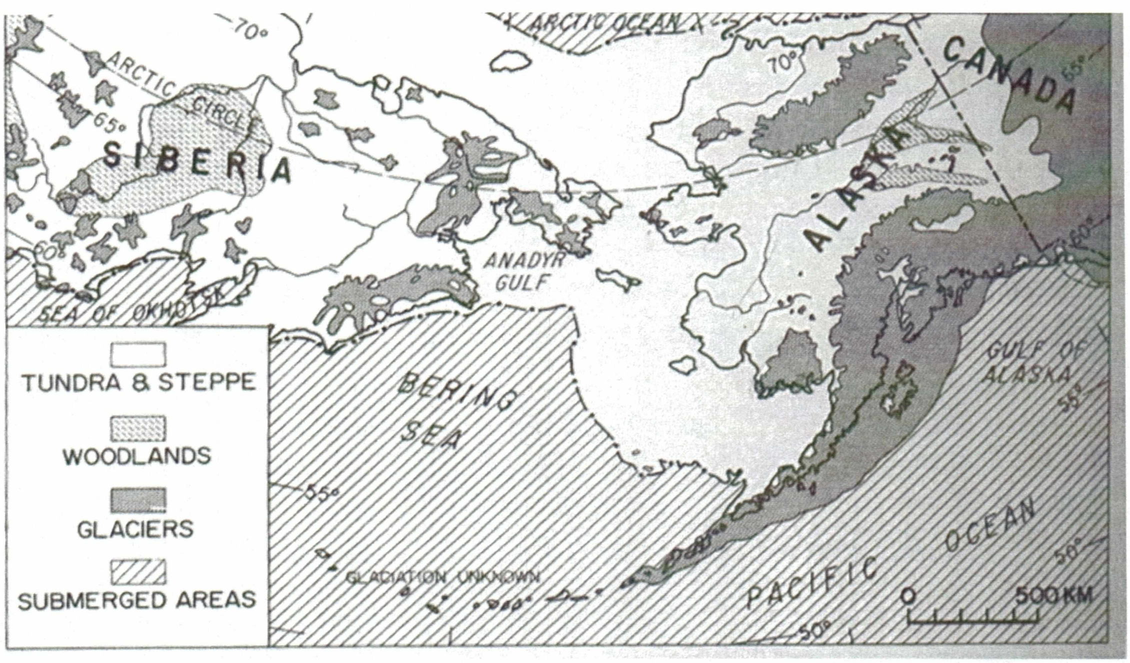


Figure 4.23 Paleogeography of Beringia during the height of the Illinoian or Riss glaciation (After Hopkins, 1982)

Chapter 5

CONCLUSIONS AND FUTURE WORK

The major conclusions of this study are:

1. The seismic surveys were of limited use as they could not resolve the upper 1-2 m of the seafloor lithology. This was probably due to the use of a low frequency signal and due to the low resolving power of the hydrophones.
2. Penetration of the vibracore was not deeper than 1 m, probably because of the hard substrate.
3. Geostatistical analysis of the data indicated that at least 20 x 10^6 m^3 of gravel above 90 % cut-off is present in the upper 0.5 m of the seafloor. The CBR value of 90 seems to indicate that the gravel is of good quality for use in foundation fill.
4. The paleogeographic history was a determining factor in gravel presence in the nearshore southeast Chukchi Sea region.

The main recommendations for future sampling should take into account the following factors:

1. Sampling should be focused in the identified gravel rich zones to decrease the size of the sampling zone thus saving time and money.
2. Stratigraphic variation in size grading should be determined by coring the substrate. Based on the experience with vibra coring in the present investigation, it is not preferred and instead the rotary method of coring should be employed.

3. If coring is not possible, then bulk grab samples should be taken so that the samples are representative of the entire population.
4. Sampling should be done in equally spaced grids so that accurate variography can be performed.
5. Anisotropy in the gravel values should be taken into account in future sampling.
6. The impact of sampling and future mining on the physical and biological environment should also be assessed.
7. The physical and chemical properties of gravel suitable for various applications should be tested in accordance with ASTM and AASHTO regulations.

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Appendix A

Results of grain size analysis of cores

Table A1 Results of grain size analysis on stratigraphic samples in core ST# 6

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	0	0	0	0	0
5	9.55	62.53	25.10	2.82	27.92
10	0.54	60.33	36.31	2.82	39.13
15	1.76	51.61	42.70	3.92	46.63
20	2.78	54.45	38.79	3.98	42.77
25	1.78	55.97	38.56	3.69	42.25
30	0.88	55.00	40.71	3.40	44.11
35	1.54	42.44	50.63	5.39	56.02
40	20.06	51.89	25.34	2.71	28.05
45	2.15	30.53	64.13	3.19	67.32
50	0.35	37.54	55.77	6.34	62.11
55	0.68	25.00	69.73	4.60	74.33
60	0.83	27.10	66.91	5.15	72.07
65	0.56	31.88	62.57	4.99	67.56
70	4.50	41.60	49.20	4.71	53.91
75	0.20	37.11	59.66	3.03	62.70
80	0.24	45.79	51.41	2.56	53.97
85	1.14	40.78	54.49	3.58	58.08
90	0.68	43.30	51.94	4.09	56.03
95	0.08	49.97	46.86	3.09	49.95
100	0.39	69.87	27.68	2.06	29.74

Table A2 Results of grain size analysis on stratigraphic samples in core ST# 9

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	8.44	85.12	3.93	2.51	6.44
5	8.44	85.12	3.93	2.51	6.44
10	61.57	37.05	0.90	0.48	1.38
15	58.48	36.27	3.98	1.27	5.26
20	59.06	38.28	1.35	1.31	2.66
25	65.71	31.90	1.38	1.01	2.39
30	67.16	30.17	1.44	1.23	2.67
35	67.91	30.07	1.01	1.00	2.02
40	63.92	33.35	1.67	1.06	2.73
45	77.44	20.88	1.05	0.63	1.68

Table A3 Results of grain size analysis on stratigraphic samples in core ST# 13

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	0.30	80.85	14.80	4.06	18.85
10	0.30	80.85	14.80	4.06	18.85
15	30.01	63.91	4.90	1.19	6.09
20	48.10	48.22	2.66	1.02	3.68
25	47.07	47.39	4.39	1.14	5.53
30	43.85	51.26	3.67	1.22	4.89
35	34.09	62.13	3.14	0.64	3.78
40	38.75	56.37	4.09	0.78	4.87
45	56.43	39.28	3.16	1.12	4.28

Table A4 Results of grain size analysis on stratigraphic samples in core ST# 14

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	6.96	52.82	34.84	5.38	40.22
10	6.96	52.82	34.84	5.38	40.22
20	1.13	51.00	45.47	2.40	47.87
25	2.38	72.43	23.80	1.39	25.19
30	31.32	57.99	8.85	1.85	10.69

Table A5 Results of grain size analysis on stratigraphic samples in core ST# 15

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	0.56	76.87	19.75	2.81	22.56
5	0.56	76.87	19.75	2.81	22.56
10	16.88	77.10	5.25	0.76	6.02
15	29.25	67.67	2.44	0.65	3.08
20	27.17	68.89	2.83	1.11	3.94
25	35.37	61.90	2.01	0.71	2.72
32	53.94	43.94	1.68	0.44	2.13

Table A6 Results of grain size analysis on stratigraphic samples in core ST# 17

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	59.24	24.55	14.91	1.30	16.21
5	59.24	24.55	14.91	1.30	16.21
10	58.63	24.96	14.71	1.70	16.41
15	48.35	36.86	13.05	1.73	14.79
25	41.43	29.73	26.97	1.86	28.84

Table A7 Results of grain size analysis on stratigraphic samples in core ST# 23

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	0.00	82.85	16.05	1.10	17.15
5	0.00	82.85	16.05	1.10	17.15
10	0.00	93.21	5.72	1.07	6.79
15	2.69	90.54	5.81	0.96	6.77
20	44.47	52.12	2.22	1.19	3.41
25	64.93	31.40	3.35	0.32	3.67
30	69.40	29.23	1.12	0.25	1.37
35	70.30	28.96	0.37	0.37	0.74
40	91.20	8.22	0.45	0.13	0.58
45	94.53	5.22	0.23	0.02	0.25
50	91.43	8.08	0.39	0.11	0.49

Table A8 Results of grain size analysis on stratigraphic samples in core ST# 26

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	19.32	53.28	18.65	8.76	27.41
5	19.32	53.28	18.65	8.76	27.41
10	33.20	50.78	14.94	1.08	16.02
15	50.35	34.54	13.91	1.20	15.11
20	45.17	43.63	7.82	3.39	11.21
25	11.07	49.32	37.28	2.33	39.61
30	0.34	63.34	34.58	1.74	36.32
35	0.84	63.96	32.73	2.46	35.20
40	0.31	62.89	33.99	2.81	36.80
45	1.82	62.54	32.19	3.44	35.64
50	5.08	61.47	30.19	3.26	33.45
55	4.31	44.80	40.79	10.10	50.89
60	3.76	54.81	34.88	6.55	41.43
65	6.10	47.50	37.09	9.30	46.40

Table A9 Results of grain size analysis on stratigraphic samples in core ST# 27

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	51.87	19.92	21.10	7.11	28.21
5	51.87	19.92	21.10	7.11	28.21
10	11.82	7.74	41.73	38.71	80.44
20	9.76	8.38	71.58	10.28	81.86
30	11.43	7.57	69.08	11.92	81.00
40	17.09	16.83	39.71	26.37	66.08
50	10.30	11.47	58.27	19.96	78.23
60	10.50	7.08	58.94	23.48	82.42
73	7.44	12.73	57.32	22.51	79.83

Table A10 Results of grain size analysis on stratigraphic samples in core ST# 28

CORE SECTION,cm	GRAVEL %	SAND %	SILT %	CLAY %	MUD %
0	5.24	24.17	62.58	8.01	70.59
5	5.24	24.17	62.58	8.01	70.59
10	6.25	17.83	72.94	2.98	75.92
15	16.25	15.21	62.01	6.52	68.54
20	10.58	15.48	68.58	5.36	73.94
25	12.74	14.05	67.19	6.02	73.20
30	8.63	11.61	72.44	7.32	79.75
35	7.74	11.80	73.77	6.69	80.46
45	12.08	18.04	65.58	4.31	69.89

Appendix B

Stratigraphic variations in cores

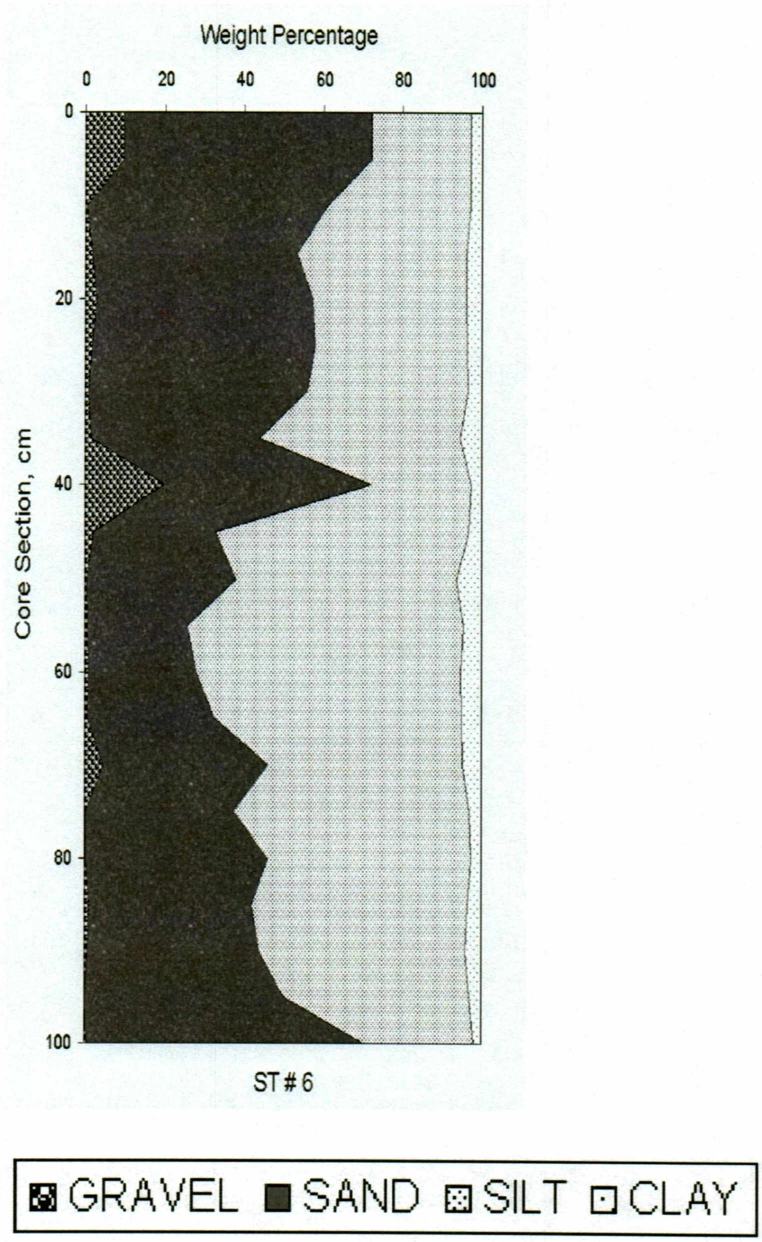


Figure B1 Stratigraphic variations in core ST#6

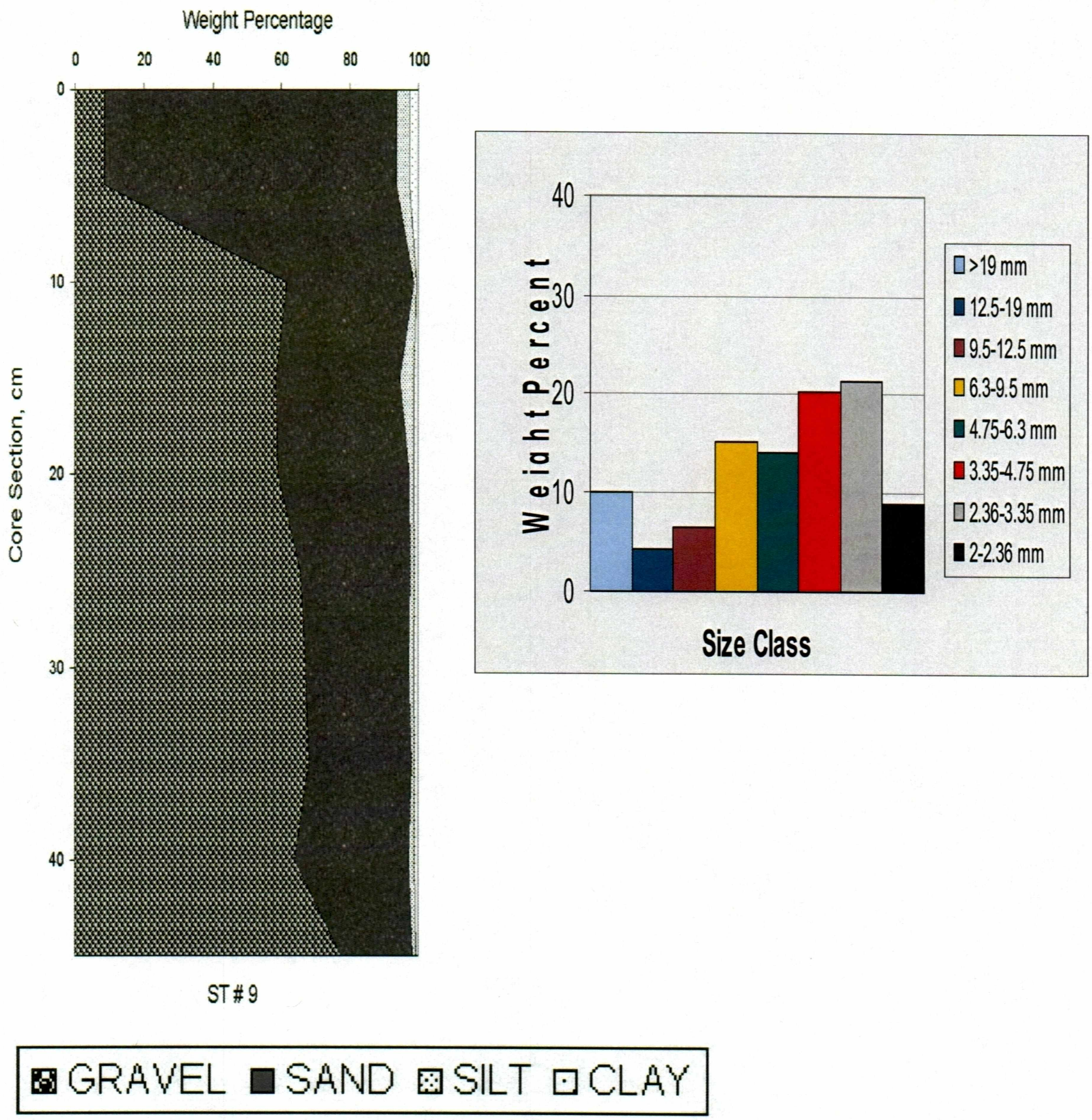


Figure B2 Stratigraphic variations in core ST#9 (left). Weight percent of gravel size classes (right).

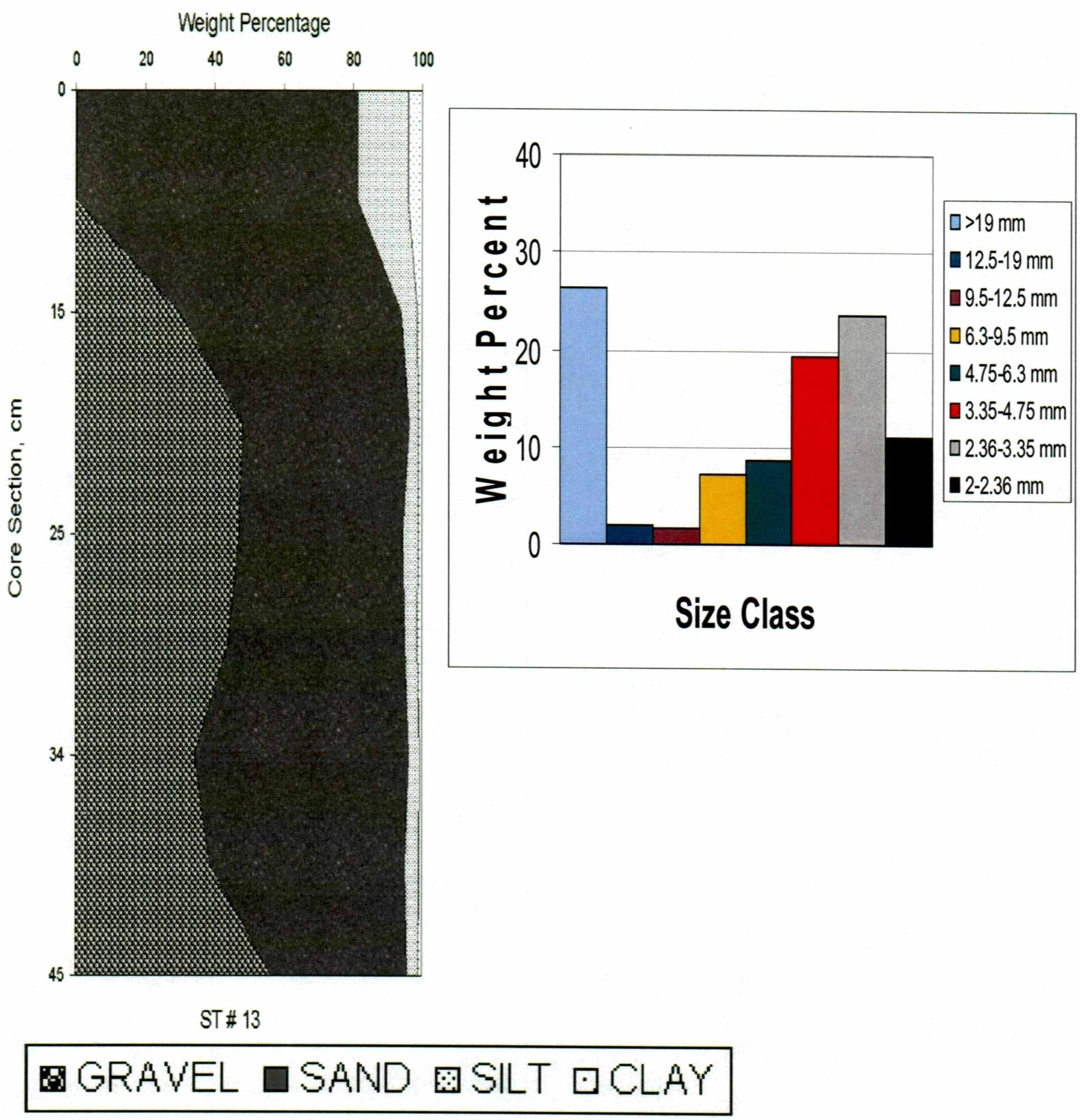


Figure B3 Stratigraphic variations in core ST#13 (left). Weight percent of gravel size classes (right).

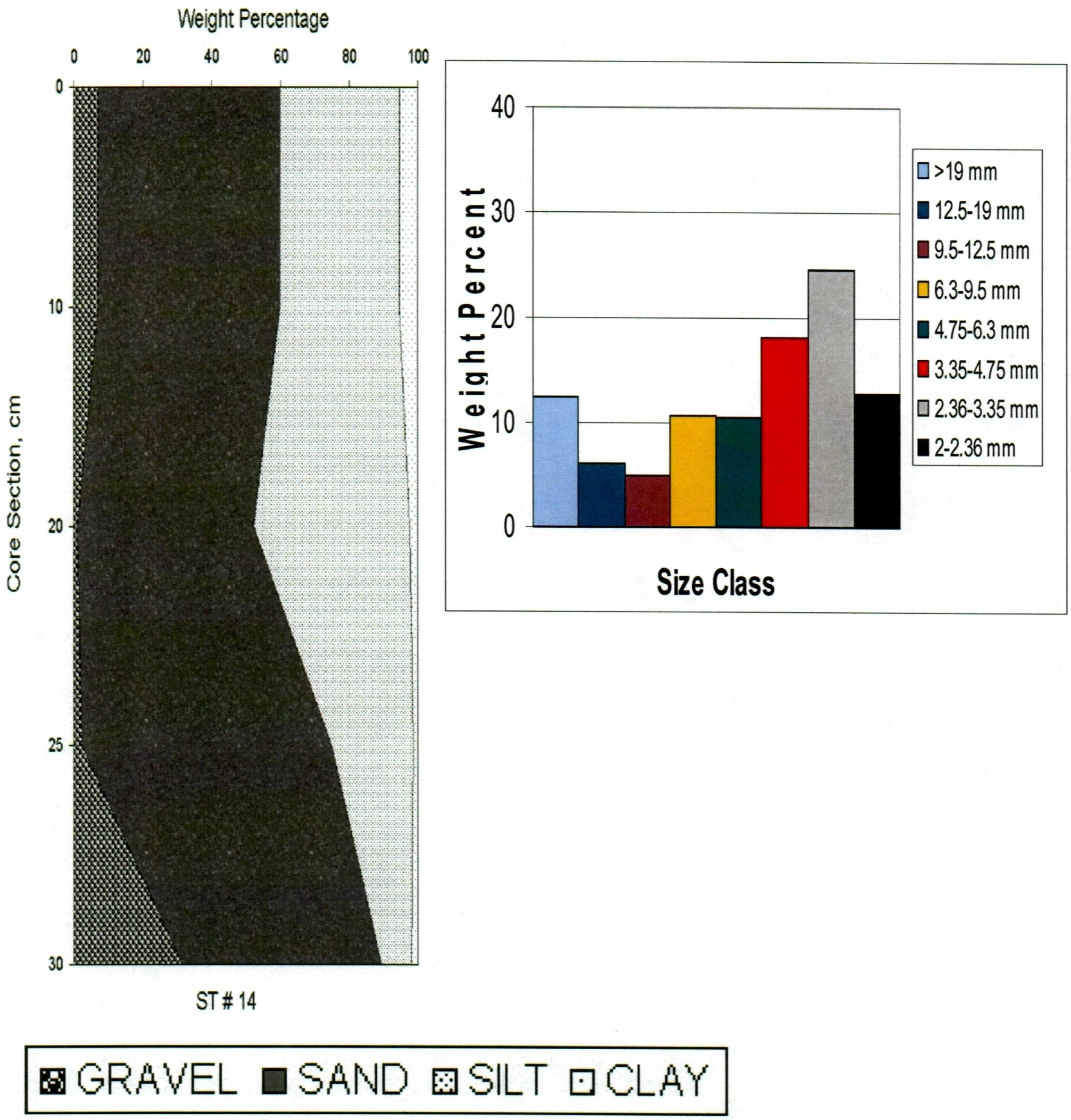


Figure B4 Stratigraphic variations in core ST#14 (left). Weight percent of gravel size classes (right).

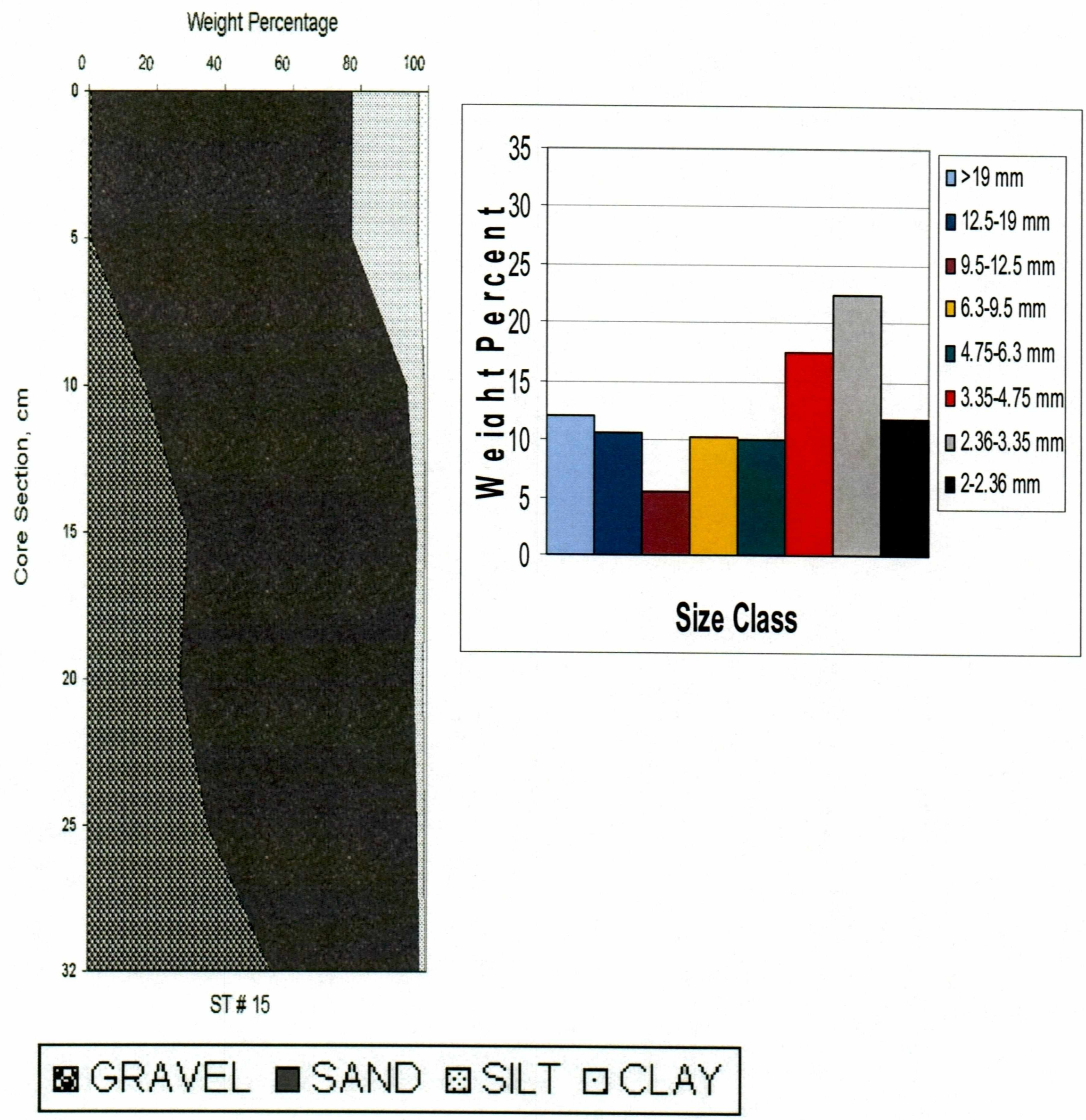


Figure B5 Stratigraphic variations in ST#15 (left). Weight percent of gravel size classes (right).

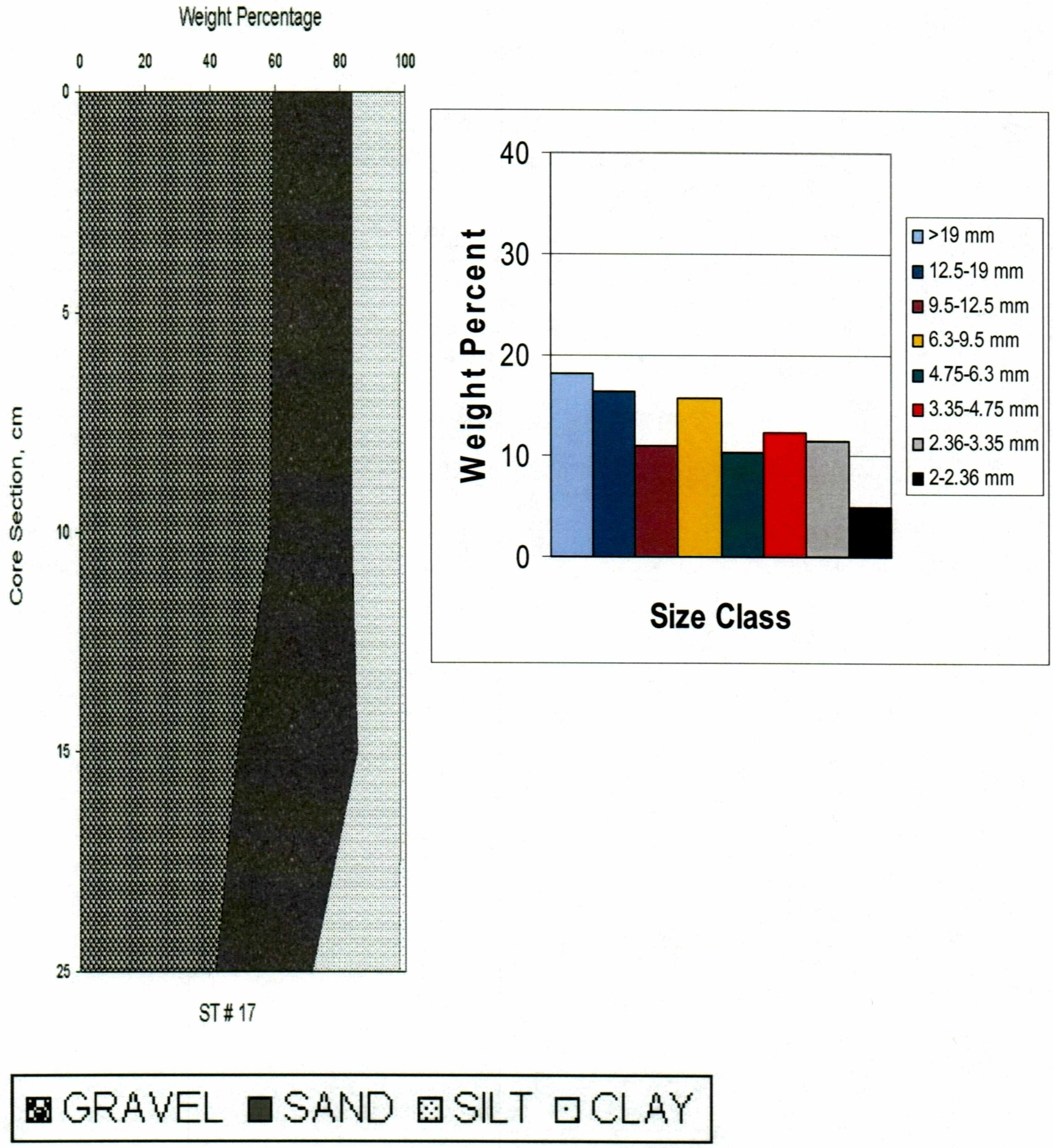


Figure B6 Stratigraphic variations ST#17 (left). Weight percent of gravel size classes (right).

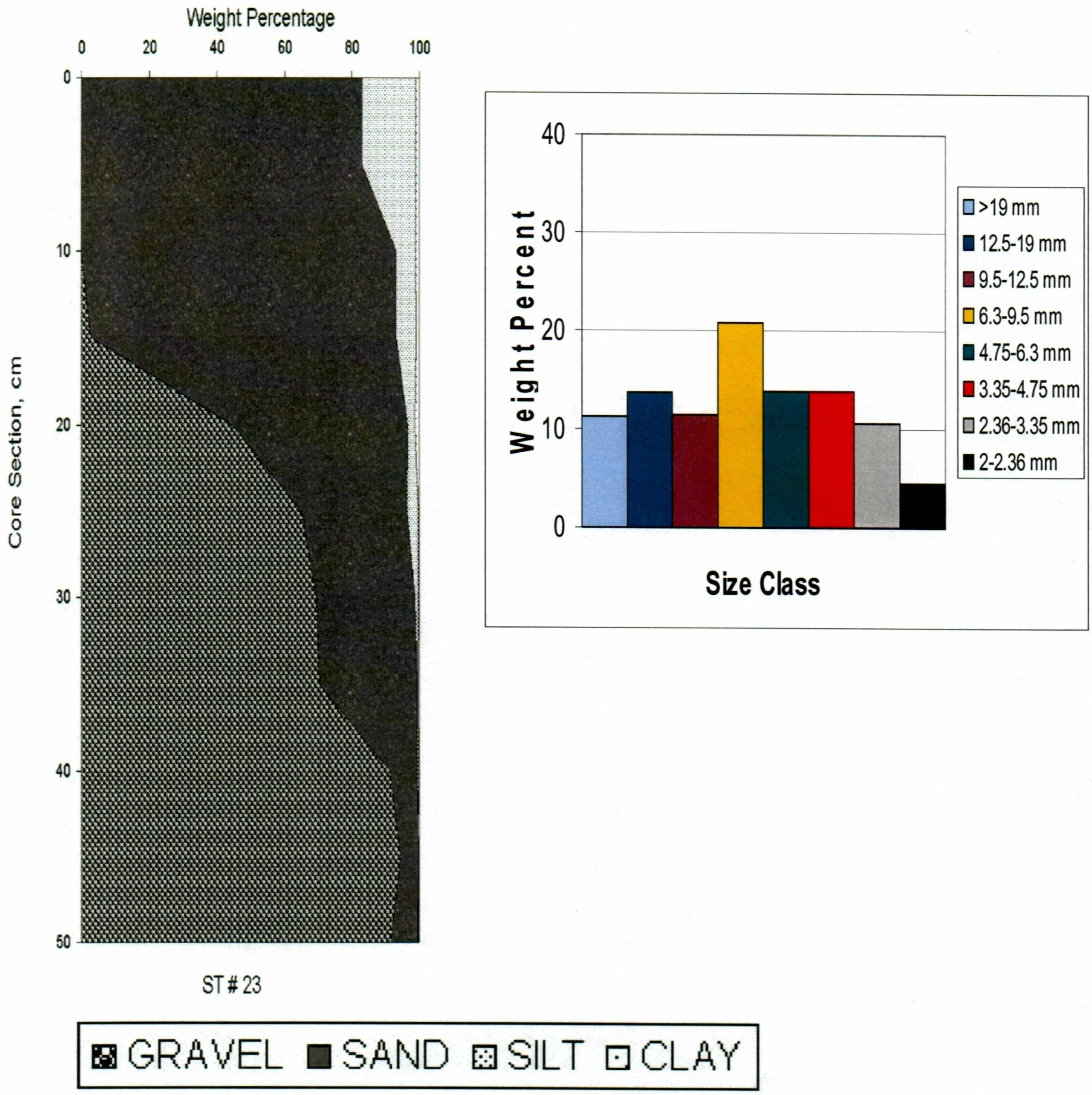
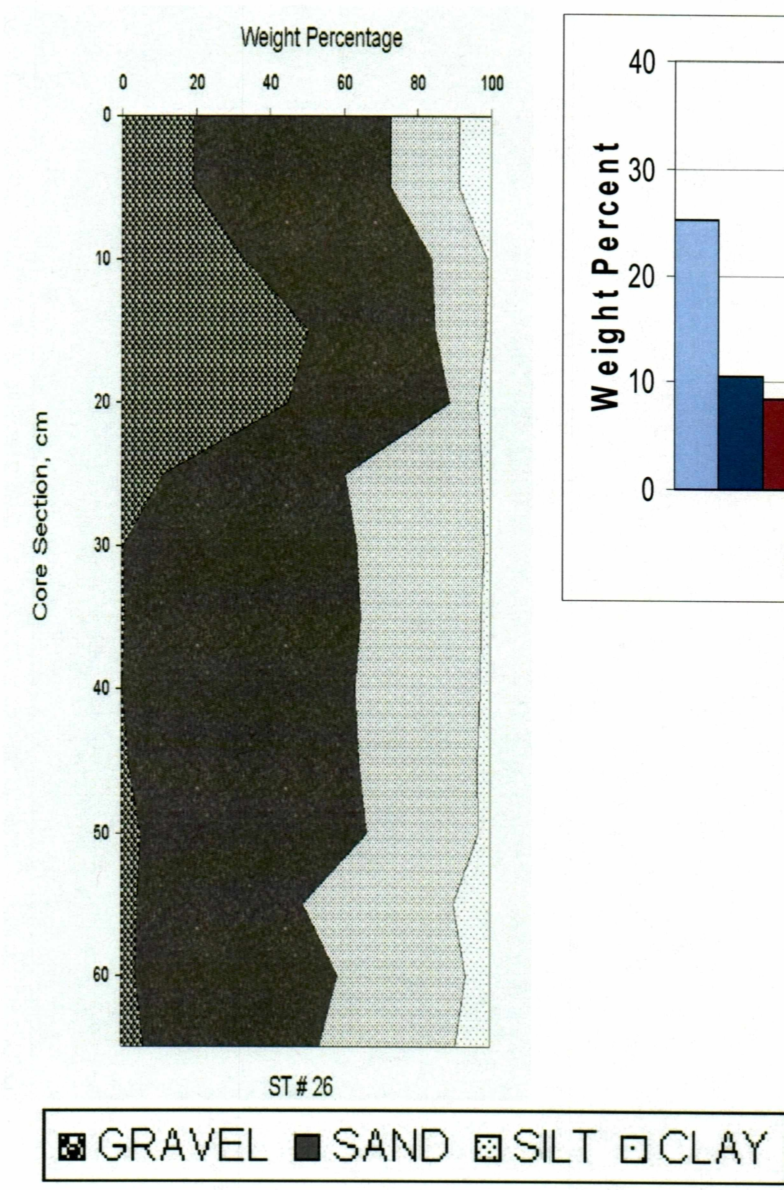


Figure B7 Stratigraphic variations in core ST#23 (left). Weight percent of gravel size classes (right).



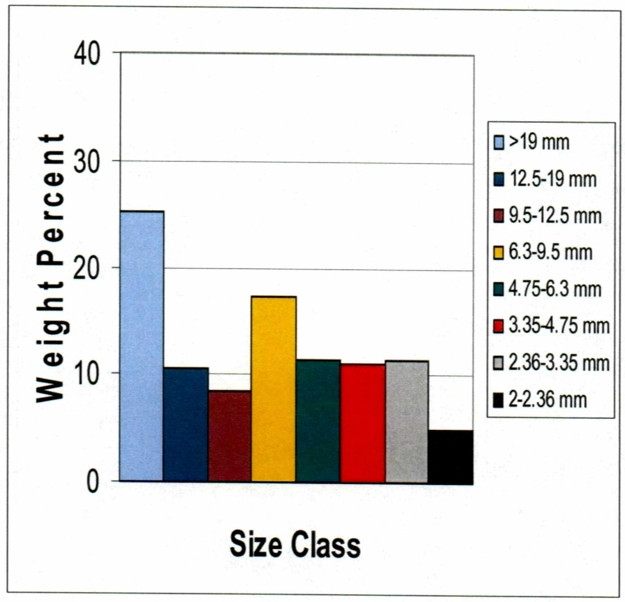
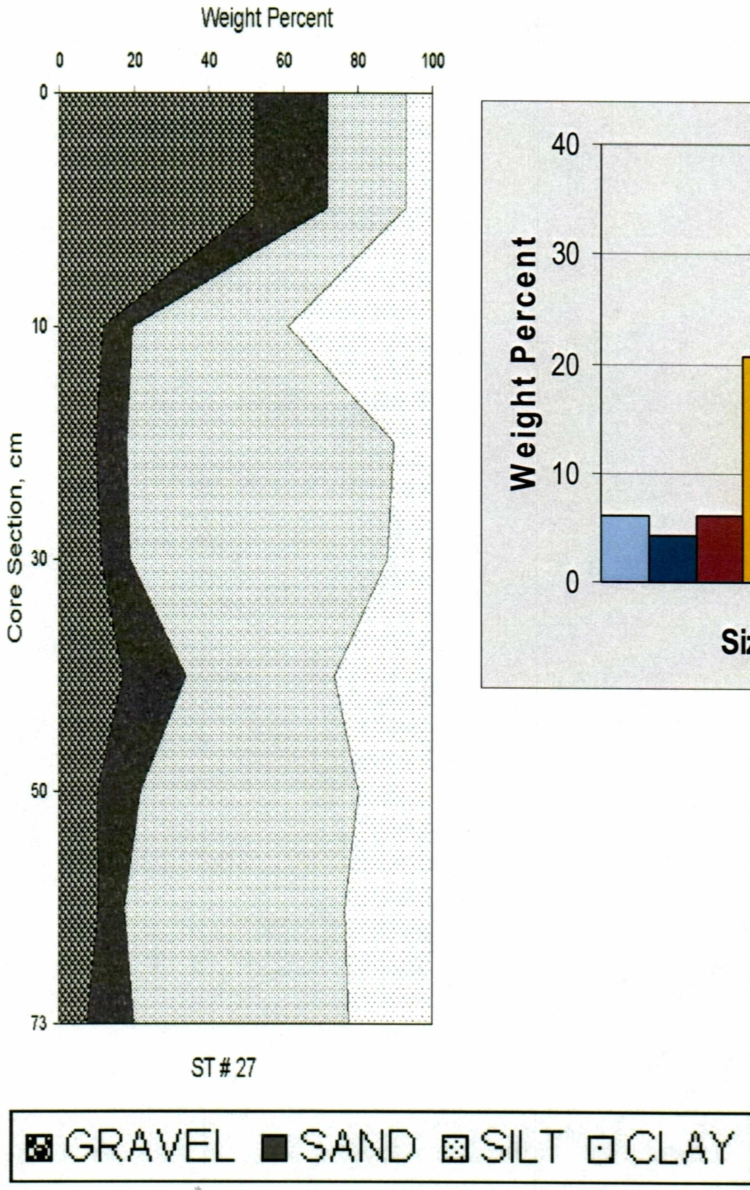


Figure B8 Stratigraphic variations in core ST#26 (left). Weight percent of gravel size classes (right).



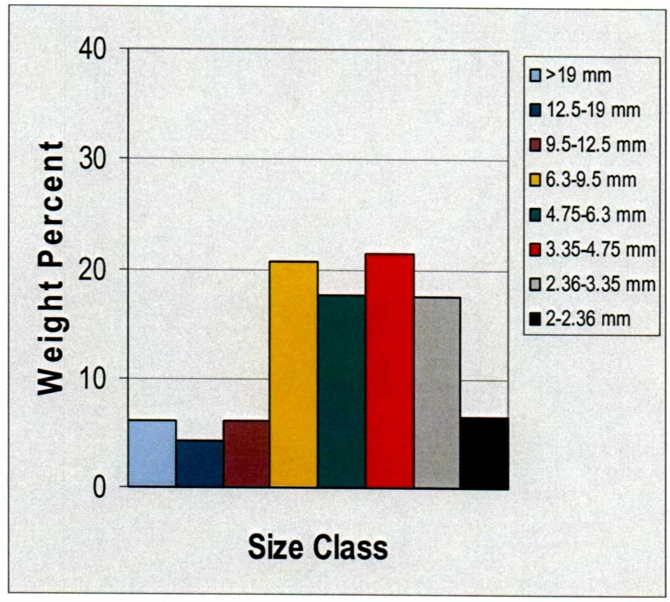


Figure B9 Stratigraphic variations in core ST#27 (left). Weight percent of gravel size classes (right).

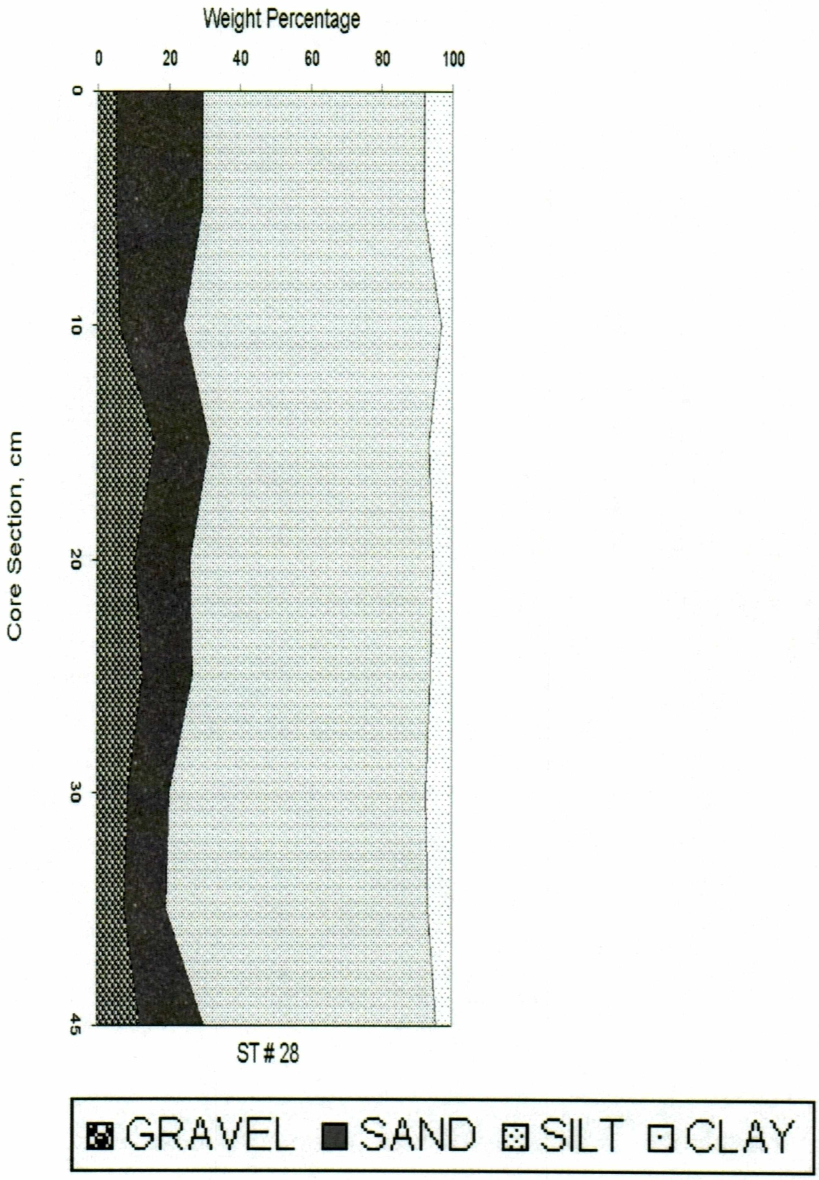
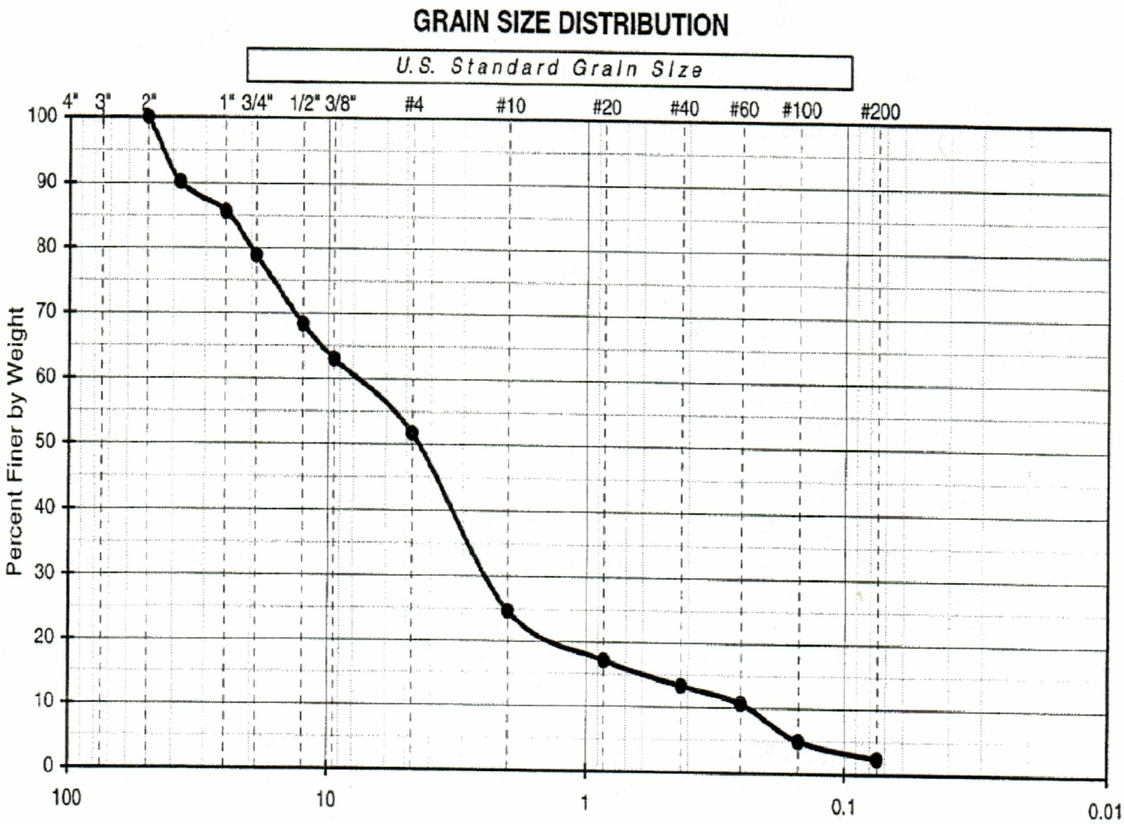


Figure B10 Stratigraphic variations in core ST#28

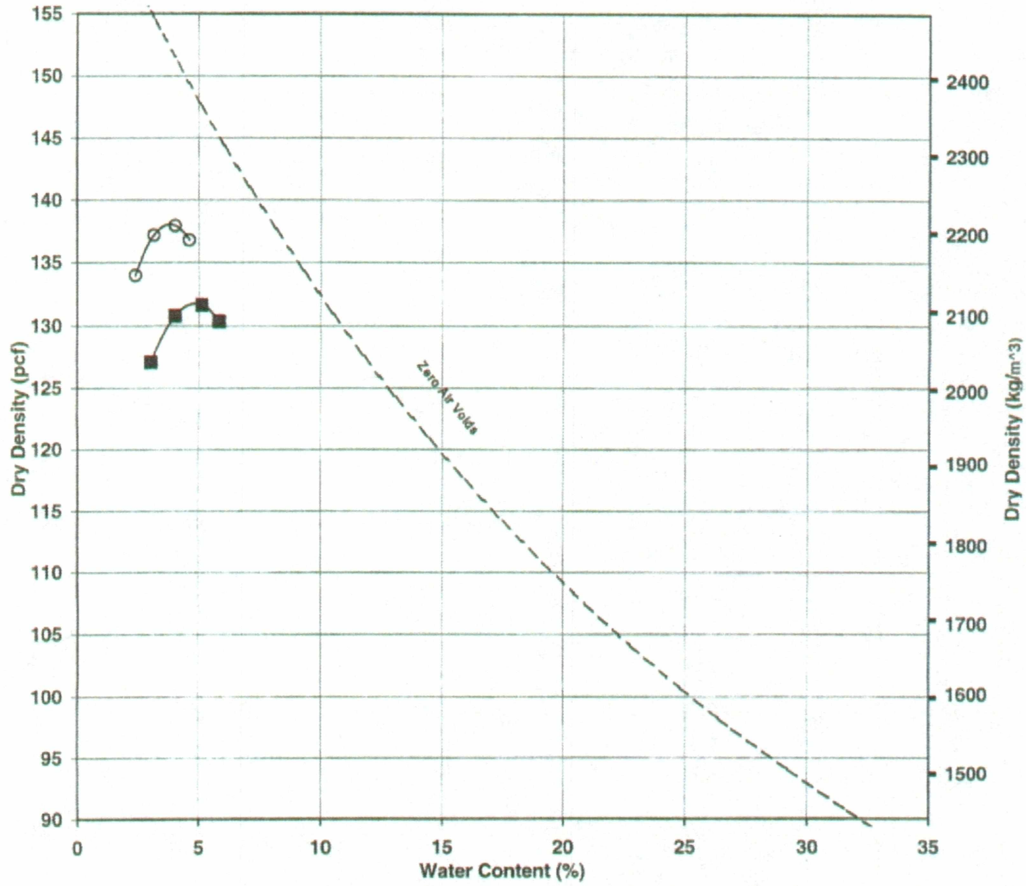
Appendix C

Results of the geotechnical analysis



Sieve Size	Percent Passing by Weight	Specification Limits Minimum	Maximum
>6"			
4"			
3"			
2.5"			
2"	100		
1.5"	90		
1"	86		
3/4"	79		
1/2"	68		
3/8"	63		
#4	52		
#10	25		
#20	17		
#40	13		
#60	11		
#100	5		
#200	2.4		

Figure C1 Grain size distribution of the composite sample used for the geotechnical analysis



Sample Description: ______________________

Sample Location: ______________________

	Symbol	Max. Dry Density (pcf)	(kg/m^3)	Moisture (%)	Percent +3/4 (19 mm)
CORRECTED	O	138.0	2210.9	3.8	21.1
	■	131.7	2110.3	4.9	21.1

Specific Gravity for +3/4-inch (19 mm) Material	2.69
Specific Gravity for Zero Air Voids Curve	2.69

Figure C2 Results of the moisture density test

Penetration (in)	Load Dial Divisions	Ring Factor N/Div	Load (Pounds)	Stress (PSI)
0.025	7	x 14.6 +12.2	114.4	36.4
0.050	11		172.8	55.0
0.075	17		260.4	82.9
0.100	22.5		340.7	108.4
0.125	28		421	134.0
0.150	35		523.2	166.5
0.175	42		625.4	199.0
0.200	49		727.6	231.6
0.300	79.5		1172.9	373.3
0.400	101		1486.8	473.2
0.500	124		1822.6	580.1
Seating Load	Dial Reset	Surcharge	Pen Stress .2" 231.6 psi	**CBR Value**
10 Lbs	1	10 LBS	Standard Stress 1500psi	**15%**
Layers	Blows per layer	Wet Density	Dry Density	Moisture Content
5	*10*	125.5	119.4	5
Test on	Condition	USCS	Effort	**Value greater@.2"**
Top	Soaked	**GP**	**Less than Standard**	**Confirmed**
Base	**Unsoaked**		Modified	

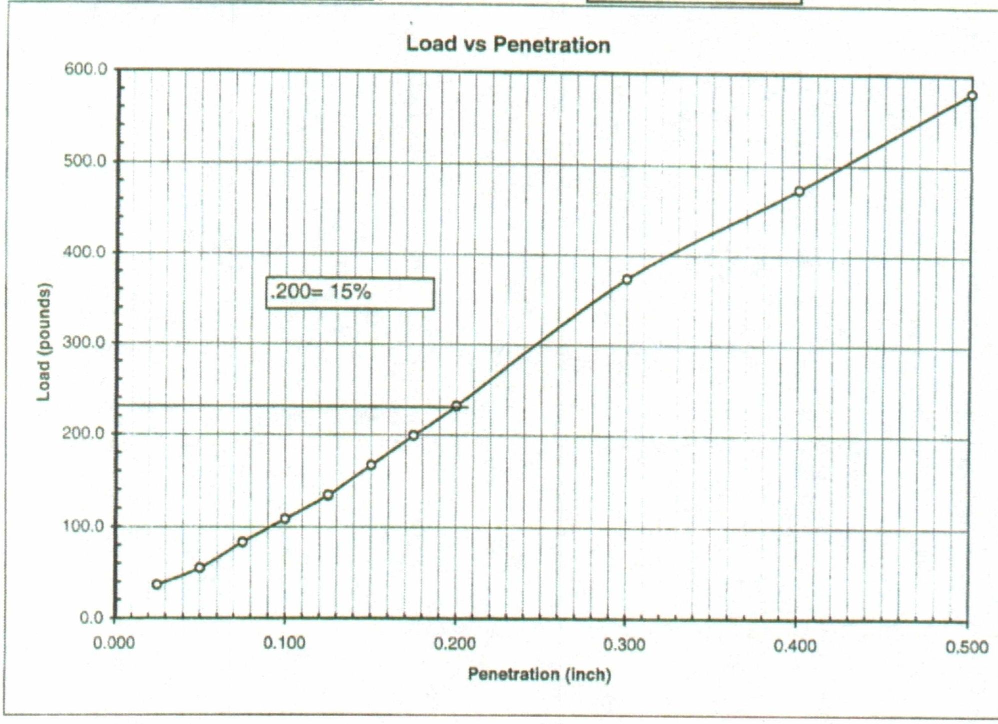


Figure C3 Results of the CBR test for 10 blows

Penetration (in)	Load Dial Divisions	Ring Factor N/Div	Load (Pounds)	Stress (PSI)
0.025	9	x 14.6 +12.2	143.6	45.7
0.050	24		362.6	115.4
0.075	40		596.2	189.8
0.100	60		888.2	282.7
0.125	84		1238.6	394.2
0.150	104		1530.6	487.1
0.175	118		1735	552.2
0.200	137		2012.4	640.5
0.300	182		2669.4	849.6
0.400	222		3253.4	1035.5
0.500	247		3618.4	1151.6
Seating Load	Dial Reset	Surcharge	Pen Stress .2" 640.5 psi	**CBR Value**
10 Lbs	1	10 LBS	Standard Stress 1500psi	**42%**
Layers	Blows per layer	Wet Density	Dry Density	Moisture Content
5	***25***	133.5	127.3	4.9
Test on	Condition	USCS	Effort	**Value greater @.2"**
Top	Soaked	**GP**	**Standard**	**Confirmed**
Base	**Unsoaked**		Modified	

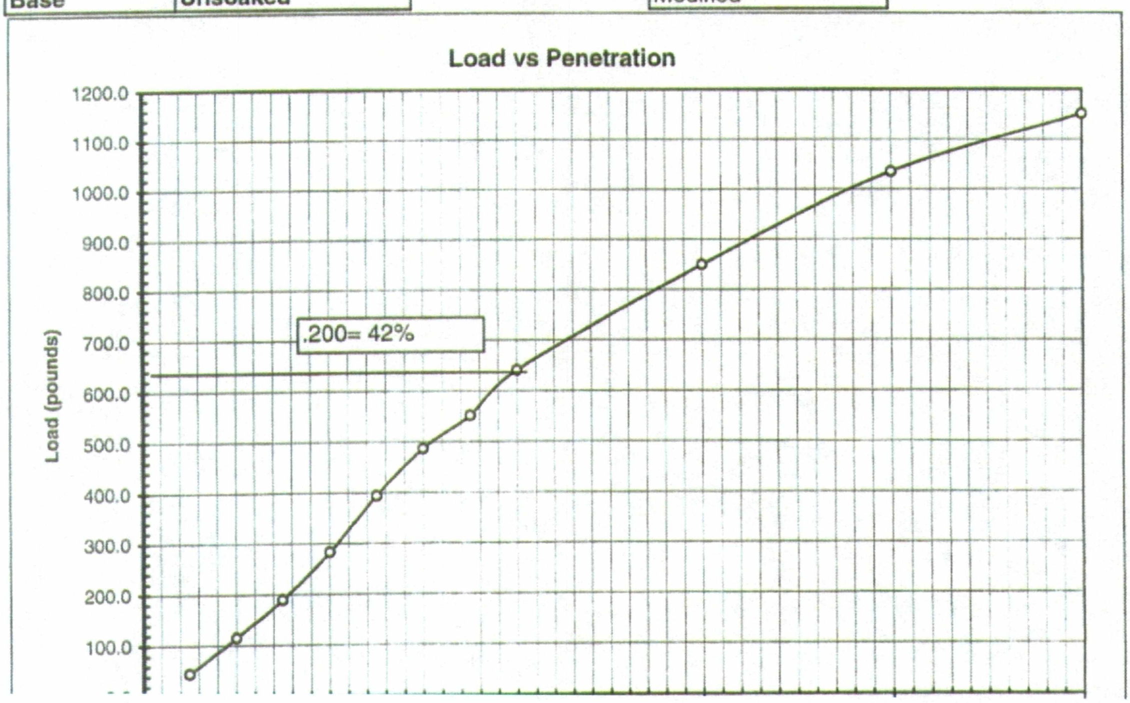


Figure C4 Results of the CBR test for 25 blows

Penetration (in)	Load Dial Divisions	Ring Factor N/Div	Load (Pounds)	Stress (PSI)
0.025	29	x 14.6 +12.2	435.6	138.6
0.050	55		815.2	259.5
0.075	104		1530.6	487.1
0.100	145		2129.2	677.7
0.125	182		2669.4	849.6
0.150	216		3165.8	1007.6
0.175	256		3749.8	1193.4
0.200	292		4275.4	1360.7
0.300	439		6421.6	2043.8
0.400	500		7312.2	2327.2
0.500	516		7545.8	2401.6
Seating Load	Dial Reset	Surcharge	Pen Stress@.2 1360.7 psi	**CBR Value**
10 Lbs	1	10 LBS	Standard Stress1500psi	**91%**
Layers	Blows per layer	Wet Density	Dry Density	Moisture Content
5	***56***	138.2	131.7	4.9
Test on	Condition	USCS	Effort	**Value greater@.2"**
Top	Soaked	**GP**	Standard	**Confirmed**
Base	**Unsoaked**		**Modified**	

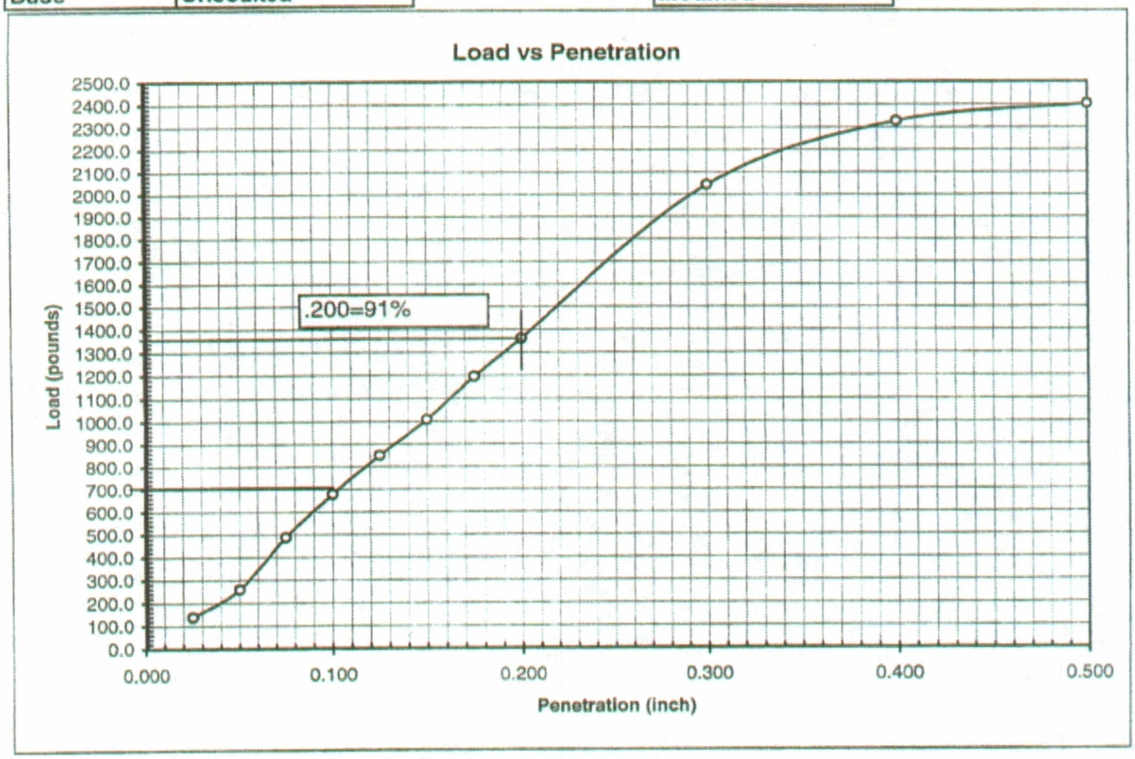


Figure C5 Results of the CBR test for 56 blows

Compactive Effort Ft-lbf/ft3	Blows per layer X 5	Wet Density PCF	Dry Density PCF	Moisture %	Corrected CBR
4960	10	125.5	119.4	5.0	15
12400	25	133.5	127.3	4.9	42
56000	56	138.2	131.7	4.9	91

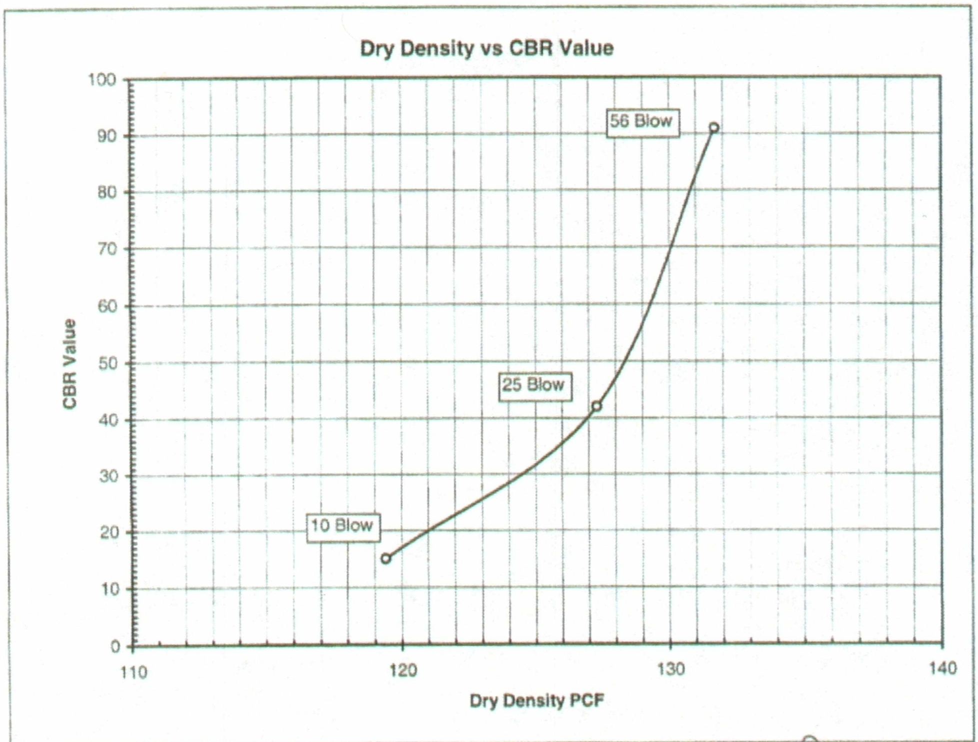


Figure C6 Results of the CBR study